FINAL TECHNICAL REPORT

INTEGRATED RESTORATION STRATEGIES TOWARDS WEED CONTROL ON WESTERN RANGELANDS

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EXECUTIVE SUMMARY

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Cheatgrass (*Bromus tectorum*) dominates 3 million acres, has heavily infested 17 million acres, and threatens another 60 million acres of rangelands in the Great Basin of western North America. An exotic annual, cheatgrass produces prolific seed, is highly competitive, and perpetuates large, frequent fires. These characteristics accelerate the loss of perennial species, increase cheatgrass dominance, and facilitate invasion of other rangeland weeds. The change from perennial to annual dominance and the altered fire cycle result in "vegetation conversion" making it difficult to restore native vegetation.

In 2003, we began three experiments to control cheatgrass and other weeds and to restore native species on western rangelands with the intention of: (1) controlling cheatgrass by reducing its seed production and competitive ability; and (2) investigating whether "transitional communities" facilitate restoration of native plants. We established two common experiments at eight sites in Nevada, Oregon, Idaho, and Utah plus a third, large-scale experiment in Nevada. Experiment 1 (Transition Species) tested establishment of 25 seed varieties for their ability to compete with cheatgrass. Experiment 2 (Functional Groups) used six native species with different growth forms to examine: (1) how different growth forms reduce cheatgrass individually compared to a mix of species; and (2) if decreased soil N availability decreases cheatgrass competition. Experiment 3 (Management Options) investigated prescribed fire and herbicide applied at a larger scale (12-acre or 5-ha plots) to reduce cheatgrass density and seed bank. All sites were originally Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and native bunchgrass communities, but had converted to essentially cheatgrass monocultures. We repeated the first two experiments in 2003 and 2004, and established the third experiment in 2004. Results from these experiments and our companion studies provide important ecological and practical information for land managers as they try to control cheatgrass and other rangeland weeds and to restore native species on western rangelands.

An important practical outcome of our studies is a series of modifications to the Truax Rough Rider Rangeland drill to further improve the effectiveness of the drill for both row and broadcast seeding. Major modifications include: (1) re-design of seed drop tubes and boots to ensure a smooth, clear flow of seed from the seed box to the ground; (2) wider disc opening for seed to drop into; (3) press wheel adjustment for more accurate closing of soil behind the discs; (4) flute adjustment crank wheel to improve calibration; (5) addition of windshields to reduce seed loss during windy conditions; and (6) addition of broadcast seeders to alternate rows to facilitate planting shallow-seeded species and deep-seeded species in a single operation. These changes are being implemented by the manufacturer, resulting in a rangeland drill that is a vast improvement over older rangeland drills.

Soil organisms play vital roles in executing ecosystem processes, and our work is the first comprehensive look at belowground community dynamics in cheatgrass-dominated areas of the Wyoming big sagebrush biome. We found that soil communities were strongly patterned by site differences, and those differences could be best explained by soil pH and surface cover type. Treatment effects were not detectable when all sites were analyzed together, but we did see some effects of the sugar treatment in Experiment 2 on microbial community structure when sites were examined individually. Our initial analysis of phospholipid fatty acid (PLFA) biomarkers indicates a large increase in fungal biomarkers with sugar application that lasts at least throughout the growing season. This result is significant because other work has shown that fungal abundance decreases when the dominant plant species changes from sagebrush to cheatgrass. As a restoration tool, applying sugar may have the added benefit of not just limiting the nitrogen supply for cheatgrass, but helping to re-establish the fungal component of the soil ecosystem. However, it is important to note that we have not yet assessed which fungal groups are changing with sugar application, so this speculation must be taken with caution. Finally, we saw no plant species effects on microbial or nematode community patterns at any of the sites.

Our research team also examined changes in soil morphology and the distribution and composition of soil organic matter (SOM) associated with cheatgrass invasion of Wyoming big sagebrush communities. Comparison of soil morphological characteristics for the top three horizons across sites showed that sagebrush A horizons were consistently slightly thicker than those under annual grasses. Soils beneath the annual grasses have significantly higher silt and clay contents than the sagebrush sites, perhaps a result of the relatively dense, continuous vegetation cover capturing more wind-blown sediments. Soils of annual grass sites also consistently have higher contents of mineral N as well as mineral N occurring as NO_3-N, suggesting that the annual grasses create a more mineralizing environment than their sagebrush counterparts, possibly due to relatively high annual inputs of more decomposable litter and roots deposited on or near a somewhat more aerated soil surface.

Results from soil nutrient analyses indicated that sucrose application greatly reduced nitrate availability for at least 1 year following application for all sites except Utah. For the Utah sites, sucrose application was ineffective in reducing NO_3^- availability because the presence of free calcium carbonate in these calcareous soils likely fostered stable Ca-humates, which are resistant to mineralization. We also observed reductions in ortho-P availability due to sucrose application, and like NO_3^-, is likely due to microbial immobilization. Manganese was also reduced by the sugar application on some sites, and given the importance of Mn in the water-splitting reaction in photosynthesis and electron transport, the reductions in Mn availability may influence plant growth. Finally, we observed that herbicide application resulted in a general increase in soil nutrient availability.

Many native and introduced grass species from numerous functional groups are available for restoration purposes, and the overall objective of Experiment 1 was to identify promising plant materials to use to transition from cheatgrass dominance to a diverse, native plant community. Here we report on 21 accessions of grasses, forbs, and shrubs planted on 8 sites in the Great Basin and seeded in two successive years. Differences occurred among accessions within a species. CD II crested wheatgrass was superior in 14 of 40 comparisons, and Vavilov was superior in none. Shaniko Plateau squirreltail was superior in 10 of 40 comparisons, and Sand Hollow was superior in 2. Critana thickspike wheatgrass was superior in 12 of 40 comparisons, and Bannock was superior in none. SRDP Snake River wheatgrass was superior in 5 of 40 comparisons, and Secar was superior in 1. Trailhead was superior in 2 of 35 comparisons, and Magnar was superior in none. Based on extreme high or low position over all comparisons, rank of bluegrasses was: Sherman (highest), High Plains, Mountain Home, and Hanford (lowest). Overall rank of bluebunch wheatgrasses was Anatone (highest), Columbia, P-7, and Goldar (lowest). Mountain rye outperformed the other cereals, which were relatively similar to one another. Using CD II as a benchmark to identify superior accessions, 3 accessions of bluebunch wheatgrass (Anatone, P-7, and Columbia) and Critana thickspike wheatgrass were native species that performed as well as CD II on 2 or more sites.

Experiment 2 investigated if reducing soil nitrogen availability can tip the balance of competition in favor of the native species and hence promote their establishment and if a range of functional types (grasses and forbs, early season and late season, deep rooted and shallow rooted) would pre-empt resources from cheatgrass and thus reduce its competitive dominance. In the first year after seeding, sucrose addition resulted in significantly less cheatgrass, smaller cheatgrass plants, and fewer seeds produced per plant and per unit ground area. Different target species also affected cheatgrass plant size such that cheatgrass plants growing with Vavilov wheatgrass or in control (unseeded) plots were the largest and cheatgrass plants growing with sagebrush were the smallest. In the second season after sucrose application, individual cheatgrass plants were slightly larger and produced more seeds in plots where sucrose had been previously added. Because sucrose resulted in lower cheatgrass density in the second season, biomass and seed production per unit ground area were similar on sugared and non-sugared plots during the second growing season after sugar application. The presence of cheatgrass significantly lowered soil moisture, but sugar-treated plots had increased soil moisture, possibly due to the negative effect of sucrose on other plant growth (and thus water use). Because the sucrose effect was short-lived, applying sucrose for two seasons in a row may possibly suppress cheatgrass more successfully.

In Experiment 2, we also investigated if seeding density had a direct effect on the establishment of cheatgrass and perennial species and if increasing density of cheatgrass had a negative effect on target perennials establishment. Our results suggest that when seed availability was less limiting (i.e., when seeding rate was the highest), perennial seedlings were able to establish and coexist with cheatgrass if cheatgrass density did not exceed more than ~300 plants m^{-2}. At higher cheatgrass densities, native seedling establishment declined. As indicated in the previous paragraph, sucrose application had a significant negative effect on cheatgrass aboveground biomass during the first growing season, but this reduction was only evident when cheatgrass seeding rates were <300 seeds m^{-2}; no differences in cheatgrass biomass were observed between sucrose treatments when seeding rates were higher. Cheatgrass was also affected by its own seed availability as increasing seeding rates resulted in higher densities. Although soil data for all the individual treatment combinations was not available, cheatgrass responses suggest increasing resource limitation towards higher cheatgrass seeding rates. The pattern observed in the control plots during the first growing season indicates that *B. tectorum* plants growing in low densities were not likely resource-limited because they were able to grow larger, producing more individual photosynthetic biomass and seeds than those growing at the highest density. Our results indicate that the seedlings of the perennial target species that established primarily during the first growing season did not have any significant effect on cheatgrass performance, but sucrose application did not have such a clear impact on the emergence and establishment of either the perennial native species or Vavilov wheatgrass. Given (1) the lack of reproducing native perennial individuals in invaded ecosystems, (2) the depleted seed banks of those species, and (3) the positive responses obtained when seeds were added, a continuous source of native seeds over time seems critical to promote ecosystem recovery. Continuity of the native propagules influx may be more crucial for the recruitment process than the total amount of seeds entering the system in a given year. Our results suggest that given adequate environmental conditions and continuous seed availability, *Artemisia tridentata*, *Achillea millefolium*, *Poa secunda*, *Pseudoroegneria spicata*, and *Elymus multisetus* can establish in the neighborhood of cheatgrass.

Coincident with the continued expansion of cheatgrass in the western US is a growing problem of invasion by secondary weeds. These weeds are considered more noxious than cheatgrass, and it has been speculated that cheatgrass may be helping to facilitate these invasions. We found no evidence of any difference among Siberian wheatgrass, cheatgrass, or the native mixture in their abilities to reduce establishment of medusahead, either with or without the addition of sugar. However, sugar application was found to have a significant negative effect on the establishment of medusahead seedlings two years after planting. Evidence that the secondary weeds compete with cheatgrass also occurred in our studies. For example, the mean number of knapweed seedlings established per plot when cheatgrass was present was lower than that when cheatgrass was absent. We found no evidence for cheatgrass facilitation of medusahead or of knapweed in our studies, although we note that we only examined one aspect of the facilitation question because all of our studies were conducted on lands currently occupied by infestations of cheatgrass. We also found that establishment of Siberian wheatgrass did not differ from that of the native mixture. The addition of carbon in the form of sugar appeared to be more of a factor in reducing establishment for the two invasive annual grasses, cheatgrass and medusahead, than it was for squarrose knapweed.

One of the unique and powerful aspects of this project is the distribution of experimental units across four states in the Great Basin. Although this distribution of sites across a large region gives us the ability to better understand ecological interactions and to generalize our results over a broad area, it also brings challenges in terms of data synthesis, analysis and interpretation. To better integrate and interpret our results, we initiated 3 statistical approaches to data analyses: (1) mixed linear models with composite predictor variables; (2) meta-analysis; and (3) structural equation modeling. Although we are still early in our attempts to create general models across sites in this study, we have some promising outcomes. First, we were able to compress our many environmental covariates into a reduced number of composite variables and produce an informative mixed ANOVA model. Analyzing the data in this way highlighted the potential importance of soil nutrients and precipitation in explaining differences in results among sites, accounted for the potential competitive relationship between our seeded species and background vegetation, and also helped clarify the significance of our experimental treatments in the light of environmental variation. Second, our meta-analysis showed that the two iterations of Experiment 2 had very similar results: a significant negative effect size of sugar application on cheatgrass seed production per plant. Interestingly, most of the variation in outcome was due to differences in effect size at different sites (in particular, a strong negative effect size at Eden Valley NV, and a less negative effect size at Cindercone Butte ID and Succor Creek OR).

Experiment 3 was designed to investigate the effectiveness of different restoration treatments to control cheatgrass competition and its prolific seed production at a management-level scale. Four potential methods to control cheatgrass were investigated: (1) experimental seeding without treatment (*i.e.* seeded control); (2) true control to test for the natural recovery of vegetation after fencing (*i.e.* unseeded control); (3) a seed-burn-seed treatment targeted to reduce both the cheatgrass seed bank and cheatgrass' access to available soil N; and (4) a herbicide treatment to serve as an experimental reference point. Following experimental treatments, 1 of 2 seed mixtures was applied: (a) 6 accessions that performed well in Experiment 1 and were thought to be suitable for the Experiment 3 restoration site; and (b) the same seed mix used in Experiment 2. Our objectives were to determine: (1) if prescribed fire or herbicide treatments reduce cheatgrass competition for available soil N and seed bank and thus enhance the establishment of native species; and (2) if a transition community of competitive natives can be established more readily than a diverse community of different growth forms. The herbicide treatment reduced cheatgrass cover in the following year, and the Experiment 2 seed mix tended to reduce cheatgrass density more than that of the Experiment 1 seed mix across all plots treatments. The herbicide restoration treatment had significantly more germinants of target species than in the burn or control treatments during the first growing season after seeding, but this trend was most pronounced in Experiment 1 seedings. Soil nutrient availability was not affected by restoration treatments in the first post-treatment year. Because land managers are most concerned about long-term restoration, we plan to follow these plots over the next few years to determine if these first year results are sustained through time.

Although reports in the literature have assumed rodents negatively impact plant fitness through seed predation, more recent research demonstrates a positive role rodents can have in plant recruitment via seed caching activities. We also initiated research to gain a better understanding of the role of granivores in restoration with special attention given to seed removal (seed choice and rates of removal), the effect cheatgrass on ants and rodents, and how site treatments and seeding influence rodent communities. Results suggest a reduction in habitat suitability for these animals when sagebrush steppe is converted to cheatgrass-dominated, weedy communities. Preliminary results also indicate a marked difference in the amount of seed removed between the two habitat types, with significantly more seed removed from the sagebrush than from cheatgrass areas, as may be expected from the differences in rodent communities noted above. Additionally, we were able to detect a marked preference of total seeds removed by species among the seven seeds when presented alone (without cheatgrass in the mixture). The ranking order in the sagebrush plots is: *Achnatherum hymenoides* (Indian ricegrass), *Panicum miliaceum* (millet), *Pseudoroegneria spicata* (bluebunch wheatgrass), *Elymus elymoides* (bottle bunch squirreltail), *Leymus cinereous* (Basin wildrye), *Poa secunda* (Sandberg bluegrass), and *Bromus tectorum* (cheatgrass). The weight of target seeds removed increased as the initial density of target seed increased and decreased slightly as the initial density of *B. tectorum* increased. Although target seed harvest was negatively influenced by the initial amount of *B. tectorum* seed present in the seed combination treatment, *B. tectorum* had only marginal influence on the harvest of any target seed.

One major focus of our integrated efforts was to assess the economic and social impact of restoration based on an ecological framework developed by our group. Over the past five decades, there has been a surge in ecological research focusing on the growing threat of biological invasions from cheatgrass. However, little to no research has been conducted on the social and economic impacts of cheatgrass invasion and restoration efforts on ranching and communities supported by ranching. The economic analyses indicated that adoption of any restoration strategy negatively impacted the ranch financially over not adopting any restoration strategies for representative ranches in Oregon, Idaho, Nevada, and Utah. In some states, adoption of herbicide and the integrated restoration strategies proved economically damaging as the ranch runs the risk of going bankrupt. Moreover, the costs of adopting an aggressive, integrated strategy were higher than any of the stand alone restoration strategies. Our results also indicated that areas with greater precipitation have smaller negative financial impacts, likely because forage availability and success of restoration are greater, which that in turn influences herd size and net returns of any representative full time ranch operation. Thus, there is a tradeoff between ecological and economic benefits from restoration, and the costs of adopting restoration strategies are significantly higher compared to no restoration. To understand the social attitudes and perceptions of different stakeholders, surveys of BLM employees, ranchers, informed citizens, and interest groups were conducted to research if the different groups have different meanings of restoration and to determine key drivers that would enable current restoration strategies to be socially acceptable. There was a consistent response from BLM personnel across the four Great Basin states with regard to the existence of a scientific difference in the meaning of restoration versus rehabilitation. The ranchers, in contrast to the BLM respondents, did not think there were any major differences in the interpretations of restoration versus rehabilitation. They also felt that cheatgrass was not necessarily a "problem." The views of the ranchers indicated that their willingness to support restoration was strongly influenced by geographic (levels of precipitation) and ecological (level of cheatgrass invasion) contexts. Furthermore, there is also the possible existence of an underlying ideology that "nature's resources is meant for humans to use" in support of the rancher's views that restoration need not occur at the expense of reduced forage availability for cattle. Ranchers also listed economic costs of seeding native species and reduced land available for grazing as a result of restoration as common barriers. Interest group respondents had similar views as those of BLM personnel with regard to restoration and felt rehabilitation to be a distinctly unique ecological concept. Informed citizens were most expressive about the possible barriers and issues involving restoration projects, and educational background was significant in the nature and quality of their responses. In sum, the economic and social studies indicate that even though public rangelands are a public good, it may not be economically efficient for ranchers to support federal and state agencies in undertaking restoration. In general, while there are some private benefits from restoration, it is likely that most of the benefits accrue to society. It may be appropriate to explore the use of (or develop) cost-share mechanisms or innovative policy tools to ensure that cheatgrass control efforts are not only ecologically feasible and socially acceptable but also economically equitable.

A second major component of our integrated activities involved outreach education with a focus to increase student and public awareness of invasive species issues and to develop educational tools that convey solutions to invasive species and native plant restoration problems. First, partnerships were established with several organizations to include a unit on weed ecology, management, and research in existing K-12 teacher workshops in Idaho and Oregon. Second, a case study, *Breaking the Cheatgrass-Fire Cycle on Northern Great Basin Rangelands*, was developed for a Wildland Vegetation and Habitat Management course at Utah State University (USU) to assist students in acquiring content knowledge, process skills, and an understanding of the context and application of science to their daily lives. A final version of this case study will be sent to the National Center for Case Study Teaching in Science at the State University of New York, Buffalo, with a request to post it on their case study website. A third outreach education initiative was to provide undergraduate students at colleges and universities in or adjacent to the Great Basin with the opportunity to participate in research and education experiences associated with the IFAFS project. Our Undergraduate Research Experience Grant Program provided competitively-awarded mini-grants ($4,000) to support research experiences and a presentation at a state, regional, or national meeting of a professional society. Fourth, field tours were used to present research findings from the IFAFS project and general information about the ecology and management of Great Basin rangelands to different audiences at the project sites. Sixth, a traveling exhibit consisting of 10 panels (each 0.75m X 1.05 m) was designed to promote learning for a widely varied audience in many different settings. It will travel to middle schools as well as libraries, museums, nature centers, town halls, or other places of community gathering. Although the exhibit panels provide a tool for free-choice learning for several audiences, there are some drawbacks to focusing solely on free-choice learning opportunities. The lack of an opportunity for both preparatory and follow-up activities is a shortcoming of informal learning settings. Therefore, a teaching activity matrix was developed for middle school teachers. The matrix organizes currently available resources with activities that are well designed and can be very easily adapted to address the specific issues presented on the exhibit panels. Formative evaluations were used in the development of the third and final version of the exhibit. Finally, the World Wide Web is an environment that provides the learner freedom and opportunity for informal learning. Web pages have been organized in a manner similar to that for the traveling exhibit, but includes other items such as a glossary of terms and sidebars featuring IFAFS project personnel. The glossary is a database that is accessed by the visitor upon selecting a hyperlinked word that is unfamiliar to them. A definition will then be displayed. Our intention is to provide definitions for increased understanding while minimizing breaks in the reading process. The first version of the website will be available for evaluation by IFAFS project scientists, teachers, students, land managers, and the general public in January 2007.

Products and deliverables – Although sample and data collections only ended within the last 6 months, we have published and submitted five manuscripts that were based upon research funded in part by this project. We also expect that most of the chapters in this final report will result in additional manuscripts in the next few months. During the course of the project, we have also communicated initial results and observations to various stakeholder groups such as professional societies, university colleagues, federal agencies, land managers, and others through 18 invited presentations (includes 12 presentations at a half-day symposium that is devoted solely to this project at the 2007 Annual Meeting of the Society for Range Management), 27 contributed presentations, 4 seminars, and 10 field tours. Information about the project was also publicized through news releases to newspapers and radio and through teacher workshops. This project will also result in 6 M.S. theses and 4 Ph. D. dissertations.

Human resource development – This project provided support for and contributed to the professional development of 1 postdoctoral student, 4 Ph. D. students, and 6 M.S. students. Five of these students were female, and one was an international student. Four undergraduate students were awarded 3-month internships to work on the project. Twenty two individuals worked as full-time, permanent technical support staff on the project during at least part of the project period. In addition, 24 individuals were hired to work on the project as short-term (usually summer) support staff. Thirty one undergraduate students assisted with the field, laboratory, and outreach components of the project, and 15 individuals volunteered to work on aspects of the project. Of the total 103 individuals who participated with the project, 44% were female. Note that because of privacy constraints, we did not gather comprehensive information on ethnic background of all individuals; however, individuals of Native American, Hispanic, and Asian descent were among our project personnel.

Chapter 1 – Introduction and Project Overview

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INTRODUCTION

Invasive species are having severe ecological (Mack *et al*. 2000) and economic (Pimentel *et al*. 2005) impacts on ecosystems around the world. Invasive species can alter many ecosystem processes (Crooks 2002, Walker & Smith 1997) including: water and nutrient availability, such as form and amount of N if the soil (Evans *et al*. 2001, Sperry *et al*. 2006); primary productivity, through shifts in growth rates or efficiency of resource use; disturbance regimes, including the type, frequency, and severity of disturbances such as fire (D'Antonio 2002); and community dynamics, such as species replacements (Alvarez & Cushman 2002). The economic losses and damages by invasive plants are estimated to be ~$34 billion in the US and ~$95 billion worldwide (Pimental *et al*. 2005).

Although trade and human migrations are among the most important vectors for introducing invasive plants (Mack *et al*. 2000), similar consensus on the causal mechanism for invasiveness is lacking (Dietz & Edwards 2006). Many different hypotheses have been proposed to explain why species are invasive. Some hypotheses, such as the vacant niche hypothesis, are conceptually appealing but lack concrete evidence to support them (Mack *et al*. 2000). Others, such as the allelopathy hypothesis (Callaway & Aschehoug 2000, Bais et al. 2003), have strong evidence to support them for some specific cases, but are unlikely to be important for most plants. Understanding why a species is invasive is important because it provides insight into how to control the invasion. Because a causal mechanism that is universally applicable to all plants has not been identified to date, careful attention must be made to biological and ecological characteristics of the plants and communities of interest if control strategies are to be implemented.

Restoration of Great Basin rangelands is only marginally successful when native plant species are used (Monsen & McArthur 1995; Young 1994). Furthermore, the need for successful restoration strategies is becoming more acute. For example, over 675,000 hectares of Great Basin rangeland burned in the summer of 1999 (USDI 1999), and historical and paleoecological evidence suggest that an increase in the acreage burned each year is the trend for the future (Tausch *et al*. 1993, Gruell 1999). Several factors contribute towards this trend, but the presence of invasive species, especially cheatgrass, is accelerating this trend as well as complicating land rehabilitation efforts (MacDonald 1999). Cheatgrass greatly alters the community and fire dynamics of Great Basin rangelands by increasing the fine fuel needed to carry frequent fires (Billings 1990). If present in a community, cheatgrass usually remains a part of the herbaceous layer until a fire occurs, after which it expands its dominance by replacing fire-sensitive native shrubs and by competing successfully with grasses (Young *et al*. 1987). Thus, fire facilitates the conversion of rangelands from a perennial-dominated to an annual-dominated system (Billings 1990, Young & Evans 1973, Young *et al*. 1987). Dominance by this exotic annual grass fueled over 70% of the large fires (>5000 acres) in the Great Basin from 1980-1995 (Knapp 1998), and cheatgrass cover greater than 45% was associated with a 100% fire risk (Link *et al*. 2006). In addition, the greater responses of exotic annual grasses to increased atmospheric CO_2 suggest that invasions will only worsen in the future if the system is left unmanaged (Smith *et al*. 2000, Ziska *et al*. 2005).

Unfortunately, the conversion from native perennial communities to cheatgrass-dominated sites tends to result in a relatively stable community that differs greatly from the former vegetation (Smith *et al*. 1997). Although excessive livestock grazing accelerates this conversion (Smith *et al.* 1997), other factors, such as climate (Chambers *et al*. 2006) and soil nutrient levels (Lowe *et al*. 2003), also may be involved in the conversion from native perennial communities to cheatgrass dominance because rangelands dominated by native perennial vegetation can become dominated by cheatgrass even in the absence of grazing or fire (Svejcar & Tausch 1991). Once converted, these cheatgrass-dominated sites reduce suitable habitats for many wildlife species, accelerate erosion, provide an unpredictable forage supply for livestock, and lower the economic value for ranchers. Furthermore, secondary weeds are beginning to emerge as significant components in cheatgrass-dominated lands. For example, knapweeds (*Centaurea* spp.) now have a stronghold in central Utah and in west-central Oregon and are rapidly expanding in central Nevada, rush skeleton weed (*Chondrilla juncea* L.) is advancing in southern Idaho, and repeatedly-burned areas are susceptible to invasion by medusahead (*Taeniatherum caput-medusae* ssp. *asperum* (Sink.) Melderis) throughout the Great Basin. Thus, to decrease the ecologic and economic impacts of these invasive weeds, we need to control cheatgrass and other weeds, break the cheatgrass-induced fire cycle, and restore Great Basin rangelands with a diverse, native plant community.

Cheatgrass (*Bromus tectorum*)

Cheatgrass (*Bromus tectorum* L.) is an invasive annual grass that dominates ~2 million hectares in the Great Basin (Bradley & Mustard 2005). A member of the Poeae tribe within the Poaceae, cheatgrass has other common names (ITIS 2006): downy brome is the next most commonly used name, but downy chess and broncograss have also been used periodically in the literature. Key characteristics of cheatgrass include: an open, drooping, often highly-branched panicle that typically turns purple as seeds mature; an awned lemma, but both lemma and awns are mid-sized (10-12.5 mm and 10-17 mm long, respectively); and stems, sheaths, and leaf blades have a soft pubescence (Cronquist et al. 1977).

Cheatgrass has almost a global distribution. It is found throughout North America, including all 50 states, and much of Eurasia as well as such diverse locations as Japan, South Africa, Australia, New Zealand, Iceland, and Greenland (Carpenter & Murray 2001, PLANTS 2006). Cheatgrass is native to and commonly found in the plains of central Asia and southwesterly into the Middle East and Arabian Peninsula (Kostivkovsky & Young 2000). The western edge of its native distribution is primarily the Balkan Peninsula, although some outlying native populations appear as far west as Spain, and its northern edge is near Moscow.

Genetic work to date suggests that central Europe is a major source of genotypes in the western US (Novak & Mack 2001), although this source is somewhat surprising considereing the differences in climate between central Europe and the western US. The overall genetic diversity of cheatgrass in North America is relatively low because North American populations appear to be founded by limited introductions from disparate populations (Novak *et al*. 1991, Novak & Mack 2001). Evidence for local adaptation occurs in multiple traits in North America (Rice & Mack 1991, Meyer *et al*. 1997, 1999, 2004) despite the short time since introduction, and six variable microsatellite loci have been described (Ramakrishnan *et al*. 2002, 2004, 2006). Because *B. tectorum* is almost entirely self-pollinating, some microsatellite markers in North America have been shown to be linked to adaptive traits.

Two biological features contribute to the remarkable success of cheatgrass in the Great Basin (Smith *et al*. 1997): prolific seed production, especially under favorable conditions, and high competitive ability. Seed production by cheatgrass can be 10-100 times greater on burned sites in the first year after fire, and even though population density may be relatively small during this first year after a fire, field and modeling studies demonstrate that cheatgrass populations have an 80-90% risk of exploding to densities near 10,000 plants m^{-2} within 10 years (Young & Evans 1978; Pyke 1995). Cheatgrass competes with native species for soil water and negatively affects the water status and productivity of established perennial plants, and the reduced productivity and greater water stress experienced by the native perennials persist for at least 12 years after fire (Melgoza *et al.* 1990). Greater root elongation at low soil temperatures (Harris 1967) as well as replacement of root systems (Melgoza & Nowak 1991) likely provide the means for cheatgrass to compete for limited soil resources. Thus, strategies to enhance the restoration of Great Basin rangeland must destabilize the dominance of cheatgrass by reducing the abundance of cheatgrass seed followed by reseeding with species that are competitive with cheatgrass.

PROJECT OVERVIEW

Our integrated weed control and rangeland restoration project involved 3 experiments:

Experiment 1 investigated which of the available native plant materials are more competitive with cheatgrass, and thus may be better suited to help break the cheatgrass-fire cycle and begin the transition from exotic annual-dominated vegetation to native perennial-dominated vegetation..

Experiment 2 examined: (1) if the competitive interactions between cheatgrass and 6 native species change with soil N availability or with species mixtures; and (2) if a mix of species that differ in growth form, rooting characteristics and phenology is a viable alternative to "sugaring" soils, *i.e*. to sequester soil N.

Experiment 3 investigated the effectiveness of different restoration treatments at a larger land area scale. One of the restoration techniques (a spring herbicide treatment) was targeted at reducing the cheatgrass seed bank for the following growing season when seeded species would be growing, and a second technique examined if an annual cover crop followed by a prescribed fire can be used to both tie up soil N and reduce the cheatgrass seed bank. The experiment also contrasted if more competitive native species (identified in Experiment 1) is more effective for cheatgrass control than the suite of species that differ in growth form and phenology from Experiment 2.

More details on these experiments are given in the individual chapters of this report. In the remainder of this chapter, we provide an overview of the rationale and design for the different experiments. In addition, the project included economic and social perception analyses of restoration treatments as well as outreach programs, which also are briefly described.

Study Areas

Experiments 1 and 2 were replicated at two study areas in each of the four states of Idaho, Nevada, Oregon, and Utah for a total of 8 study areas. USDA funding was only sufficient to conduct Experiment 3 at one location: a study area in Nevada was chosen for Experiment 3. All study areas were Wyoming big sagebrush range sites with soils that were typical of the general area but had converted to cheatgrass dominance (typically <20% relative cover native perennials). Sites were fairly level and did not have a significant surface cover of rocks to facilitate drill seeding. Within each state, one study area was near the low end of the typical precipitation range for Wyoming big sagebrush (8-10" precipitation zone), and the other study area was near the high end (10-12" precipitation zone). Each study area for Experiments 1 and 2 required approximately 50 acres, and the entire study area was fenced to exclude livestock. Half of each area was used beginning in Spring 2003 and the other half beginning in Spring 2004 in order to fully replicate these two experiments in 2 consecutive years. For each half of the study area, preparation of study plots and application of herbicides occurred in the spring, with plots seeded the following fall. For both experiments, a total of approximately 8.4 acres within the 50-acre study area were treated with herbicides to completely remove cheatgrass, with 4.2 acres treated in Spring 2003 and 4.2 acres treated in Spring 2004. Herbicide treatments consisted of a spring treatment of Rodeo/Roundup and additional spot treatments as needed to control cheatgrass.

The study area for Experiment 3 required approximately 400 acres. Within the study area, approximately 45 acres were seeded in Fall 2004 with a cover crop and then burned in Fall 2005. Another 45 acres were treated with RoundUp herbicide in Spring 2005. Both areas with these prior treatments plus another 45 acres that did not receive any pre-treatment (a seeded control treatment) were seeded in Fall 2005 after the prescribed burn, with half of each area seeded with the "best" species from Experiment 1 that were suitable for the site and the other half seeded with the species used in Experiment 2. A fourth set of plots covering approximately 45 acres were used as an unseeded control treatment to monitor natural changes in vegetation.

Experiment 1: Native Plant Screening Trials

The overall objective of Experiment 1 was to identify promising plant materials to use in a transition stage from cheatgrass dominance to a diverse, native plant community. This experiment was based on the concepts of the state and transition ecological model (Westoby *et al* 1989, Chambers 2000) and determined which of the available native plant materials were more competitive with cheatgrass and thus be appropriate plant materials to use in a transition stage during restoration. For this experiment, we selected 25 plant varieties for screening, although we also allowed local BLM field offices to substitute other plant materials for up to four varieties if desired. The underlying restoration concept is to use a seed mix of the most competitive varieties of native species to suppress cheatgrass, and then at a later date follow with a seeding of other species to increase plant diversity. Two advantages of this approach are: (1) the targeted varieties are currently, widely, and commercially available (or they will be within the near future) and thus seed availability will not be a significant issue for land managers; and (2) the concept can be applied to very large acreages and thus is practical for land managers to use. The major disadvantage of this approach is that restoration is now a 2-step process, which adds additional costs and time.

Based upon availability of seed and the range site to be used, the following 21 accessions were common to all sites in all states:

- Bluebunch wheatgrass –Anatone, Columbia, Goldar, P-7
- Snake River wheatgrass – Secar, SERDP
- Sandberg bluegrass – Hanford, High Plains, Mountain Home, Sherman
- Thickspike wheatgrass – Bannock, Critana
- Squirreltail – Sand Hollow, Shaniko Plateau
- Crested wheatgrass – CDII
- Siberian wheatgrass – Vavilov
- Wheat sterile hybrids –Pioneer, Regreen, Stani
- Mountain ryegrass
- Scarlet globemallow

Some of these accessions are commercially available, whereas others are currently under development in plant materials programs. The last 4 accessions are annual grasses that may function similarly to cheatgrass and also are important for the "Seed-Burn-Seed" restoration strategy in Experiment 3. Additional details on these accessions are found in Chapter 2. For the 7 of 8 study areas where the local BLM office did not select plant varieties to include with this experiment, the following 4 accessions were used:

- Basin wildrye – Magnar, Trailhead
- Western yarrow – Eagle, Great Northern

Because of the very low germination and emergence of "Eagle" western yarrow at the Idaho and Oregon study areas after the 2003 seedings, "Orchard" Thurber's needlegrass was substituted during the 2004 seedings at the four study areas in those two states.

At each study area, 6 blocks of 25 study plots were established for each of the 2 study years using a randomized block design (**Fig. 1.1**). Half of the blocks were treated with herbicide to remove cheatgrass and provide a control reference. The other, experimental blocks are not treated, and cheatgrass was allowed to grow and compete with each variety to assess each variety's competitive ability. Each block was surrounded by a 50' buffer strip. Each plot was 10' x 20' and consisted of 10 rows of a particular accession, with each row 20' long and spaced 1' apart. Individual plots have minimal spacing between adjacent plots, and the plots on the outside of the block have a 10' buffer to the edge of the block. The minimum total area required is 390' x 410' for each study area in each

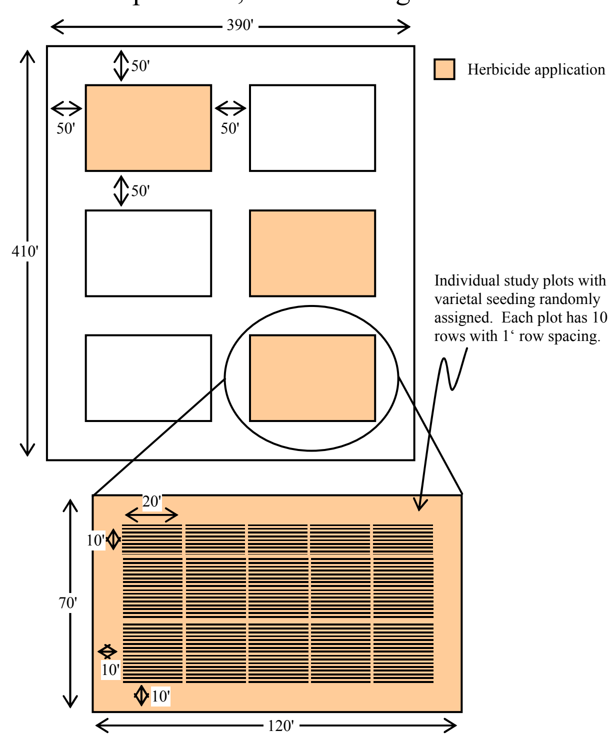

Fig. 1.1. Plot configuration for 1 year's varietal screening trials at 1 study area in Experiment 1, showing layout of 6 blocks of plots in a randomized block design at top and details of 25 plots within 1 block at bottom. Distances shown are minimum values except for row spacing.

year, or a total of ~8 acres per study area over both years for Experiment 1.

Herbicide treatments consisted of a spring treatment of Rodeo/Roundup and follow-up spot treatments as needed. Herbicide was applied to the entire treated block, *i.e.* an area of 70' x 120' for each of 3 blocks in each of 2 years at each study area, or a total of ~0.6 acres each year per study area for Experiment 1.

The generalized timeline for Experiment 1 was:

Experiment 1	2002		2003				2004				2005				2006			
	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall
Locate & prepare areas	X																	
03 seeding replicate																		
Herbicide appl.				X														
Seeding						X												
Evaluations							X	X	X	X	X	X	X	X				
04 seeding replicate																		
Herbicide appl.								X										
Seeding										X								
Evaluations											X	X	X	X	X	X	X	X

Experiment 2: Competitive Interactions

The overall objectives of Experiment 2 were to examine: (1) if the competitive interactions between cheatgrass and six native species change with soil N availability or with species mixtures; and (2) if a mix of species that differ in growth form, rooting characteristics and phenology is a viable alternative to "sugaring" soils, *i.e.* to sequester soil N. The rationale for Experiment 2 was to determine if the depletion of soil N and other soil resources can reduce the competitive success of cheatgrass. We used two techniques to deplete soil resources: (a) application of sugar to tie up soil N; and (b) a mix of native species that differ in growth form, rooting characteristics, and phenology. Many of our native range species are tolerant of low soil N, yet some previous studies have demonstrated that soil N depletion through application of sugar reduces the abundance of cheatgrass (Evans *et al.* 2001, McLendon and Redente 1991, Young *et al.* 1999). Thus, we experimentally tested this technique across the Great Basin. However, applying sugar across millions of acres does not seem practical. Thus, we also tested if the same result can be achieved with a mix of native species that differ in their growth form, rooting characteristics, and phenology.

In addition to this overall objective, selected study areas had a secondary objective. A secondary objective at one study area in Nevada was to determine how seeding densities of both cheatgrass and native species affect the competitive interactions. Secondary objectives at Idaho, one Oregon, and one Utah study areas were to determine effects of secondary weeds (rush skeletonweed in one ID study area; medusahead in the other ID and one OR, and squarrose knapweed at one UT study areas) on competitive interactions. Because of these secondary objectives, the design and layout of study plots varies slightly among the 8 study areas.

Six species for Experiment 2 were chosen because of their differences in growth form, root characteristics, and phenology:

- Sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) is a shrub that uses soil moisture all year and roots throughout the entire soil profile. Seed was locally collected.
- Bluegrass (*Poa secunda*) is a bunchgrass that uses moisture earliest in the season and the shallowest rooting. The "High Plains" variety was used.
- Squirreltail (*Elymus multisetus*) is a bunchgrass that primarily uses early season moisture and is relatively shallow rooting. The "Sand Hollow" variety was used.
- Bluebunch wheatgrass (*Pseudoroegneria spicata*) is a bunchgrass that uses mid-season moisture and has relatively extensive rooting. The "Anatone" variety was used.
- Yarrow (*Achillea millefolium*) is a rhizomatous forb that uses mid-season moisture and forms a surface mat of roots. The "Great Northern" variety was used.
- Scarlet globe mallow (*Sphaeralcea coccinea*) is a moderately drought-tolerant forb that uses early

season soil moisture. Seed from a wildland collection by the Utah Department of Wildlife Resources was used.

Although we recognize that the short study period (two years) may not allow sagebrush seedlings to become a competitively active component of the community, sagebrush is the dominant native shrub in the Great Basin and will eventually exert an important influence on competitive interactions. Thus, we included sagebrush in our Experiment 2 seed mix, which is similar to the practices used by many land managers in their reseeding programs.

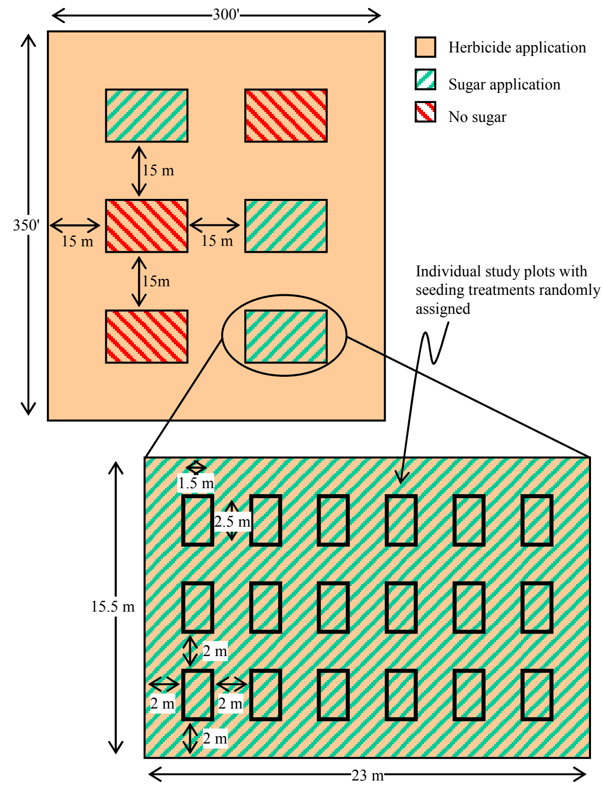

Fig. 1.2. Plot configuration for 1 year's competitive interactions studies for the main objectives of Experiment 2, showing layout of 6 blocks in a randomized block design at top and details of 18 plots within 1 block at bottom. Distances shown are minimum values.

Experiment 2 main experiment

The main experiment, designed to address the main objectives of Experiment 2, was present at each study area. Six blocks of study plots in a randomized block design were used in each of 2 consecutive years (**Fig. 1.2**). Each block was 15.5 x 23 m (50' x 75'), and blocks are separated by 15 m (50'). Each block consisted of 18 plots, each plot 1.5 x 2.5 m (5' x 8') with a 2 m (7') buffer between plots. One half of each plot is reserved for nondestructive sampling and the other half for destructive sampling. The minimum total area required is 300' x 350' for each study area in each year, or a total of ~5 acres per study area over both years. ~2.5 acres were treated with herbicides to remove all cheatgrass in Spring 2003 and an additional ~2.5 acres treated in Spring 2004.

To examine if soil N depletion reduces the competitive ability of cheatgrass, three blocks were treated with sugar and 3 left untreated. To determine if a mix of native species can accomplish the same effect, individual plots within each block received different seed mixtures in a randomized plot design. Nine perennial species seeding treatments were used, with total seeding density at 300 PLS m^{-2}. These nine perennial seeding treatments consisted of: (a) monocultures of each of 6 native species; (b) the mixture of all 6 species; (c) Vavilov Siberian wheatgrass as a contrasting introduced species; and (d) no seeds to evaluate the weed response by itself. Each perennial species treatment had two cheatgrass (*Bromus tectorum*) treatments: (a) cheatgrass seeded at 300 PLS m^{-2} (cheatgrass seed collected locally in the summer before seeding, with care taken to exclude any smut-infested seeds); and (b) none.

All plots were seeded by hand. First, individual plots were raked to roughen the soil and create 0.5-1.0 cm deep furrows. A cardboard wind barrier (1.5 x 2.5 m, about 0.6 m high) then was placed around the entire plot, and a mixture of seed and rice hulls were broadcast uniformly over the plot. The wind barrier was removed, and the seed was lightly packed into the soil with a roller.

Experiment 2 secondary experiments

The secondary objective to examine the effects of seeding densities on plant competitive interactions was examined at the high precipitation study area in Nevada in addition to the main objectives of Experiment 2 (effects of soil N depletion by sugar applications and by a mix of native species on competitive interactions). This study area had the same block treatments and all the seeding treatment combinations as the main experiment, but had additional levels of seed densities for both the native species and cheatgrass. As in the main experiment, six blocks of study plots in a randomized block experimental design were used in each of 2 consecutive years (**Fig. 1.3**). Each block was 26.5 x 29 m (87' x 95'), and blocks were separated by 15 m (50'). Each block consisted of 37 plots, each 1.5 x 2.5 m (5' x 8'), with a 2 m (7') buffer between plots. The minimum total area required for each study area in each year was 325' x 485', or a total of ~7.2 acres per study area over both years. ~3.6 acres were treated with herbicides to remove all cheatgrass in Spring 2003 and an additional ~3.6 acres treated in Spring 2004. The same 6 native perennial species and seeding procedures that were used in the main experiment were used at this study area. Each block had the following 37 seeding treatments:

- 12 plots that consisted of each native perennial seeded in monoculture at 300 PLS m^{-2}. Half of these were also seeded with cheatgrass at 300 PLS m^{-2} and half did not have cheatgrass competition. Note that these plots were identical to the monoculture set of plots in the main experiment.
- 5 plots that consisted of Vavilov Siberian wheatgrass seeded at 300 PLS m^{-2} and cheatgrass seeded at each of the following densities: 0, 150, 300, 600, and 1200 PLS m^{-2}. Note that the plots without cheatgrass and with cheatgrass at 300 PLS m^{-2} were identical to those used in the main experiment.
- 20 plots that consisted of all combinations of: native species mixture at 4 densities (0, 150, 300, and 600 PLS m^{-2}) and cheatgrass at 5 densities (0, 150, 300, 600, and 1200 PLS m^{-2}). Note that 4 of these plots were identical to those in the main experiment
- The secondary objective to examine the effects of secondary weeds on competitive interactions were examined at both study areas in Idaho, the high precipitation study area in Oregon, and the low precipitation study area in Utah. These study areas were selected for the secondary weed studies because the secondary weeds were already present in the area. The study areas had the same

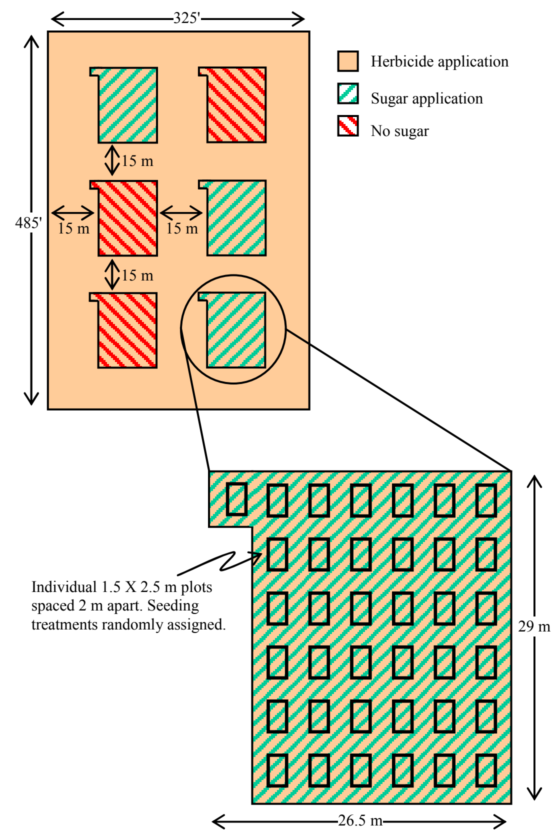

Fig. 1.3. Plot configuration for 1 year's competitive interactions studies that also investigates seeding density in Experiment 2, showing layout of 6 blocks in a randomized block design at top and details of 37 plots within 1 block at bottom. Distances shown are minimum values.

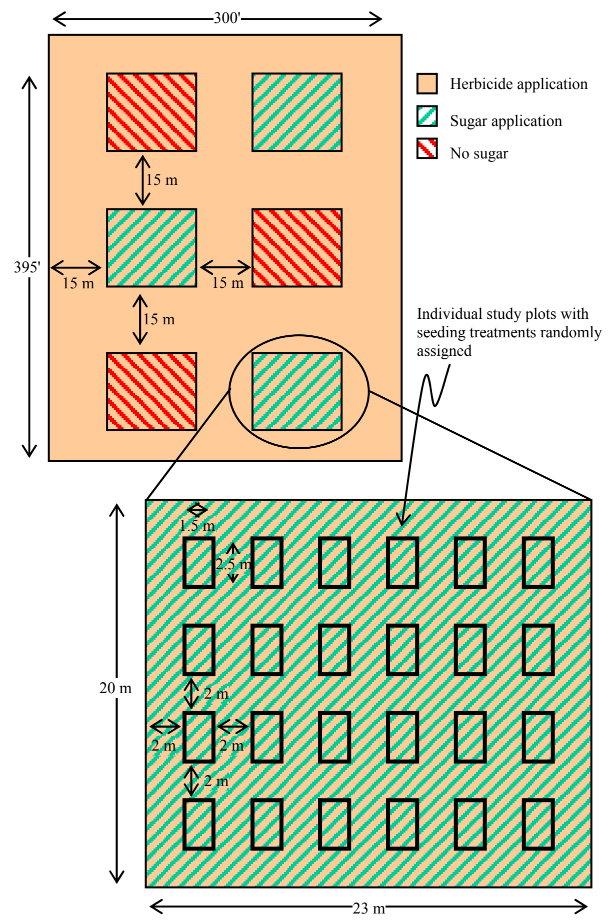

Fig. 1.4. Plot configuration for 1 year's competitive interactions studies that also investigates secondary weeds in Experiment 2, showing layout of 6 blocks in a randomized block design at top and details of 24 plots within 1 block at bottom. Distances shown are minimum values.

randomized block treatments and all the seeding treatment combinations as the main experiment, but had additional plots that had secondary weeds seeded with the perennial seed mixture and with Siberian wheatgrass (**Fig. 1.4**). Each block was 20 x 23 m (65' x 75') and consisted of 24 plots, each 1.5 x 2.5 m (5' x 8'), with a 2 m (7') buffer between plots. The minimum total area required for each study area in each year was 300' x 395', or a total of ~5.4 acres per study area over both years. ~2.7 acres were treated with herbicides to remove all cheatgrass in Spring 2003 and an additional ~2.7-acres treated in Spring 2004. Each block had the following seeding treatments:

- The same 18 seeding combinations that were used in the main experiment.
- An additional 2 plots of the native species mixture: 1 plot that also was seeded with a secondary weed (rush skeletonweed in ID; medusahead in ID and OR, and squarrose knapweed in UT) and the second that also was seeded with both the secondary weed and cheatgrass. All seeding densities were 300 PLS m^{-2}.
- An additional 2 plots of Vavilov Siberian wheatgrass: 1 plot that also was seeded with the secondary weed only and the second that also was seeded with both the secondary weed and cheatgrass. All seeding densities were 300 PLS m^{-2}.
- An additional 2 plots, 1 that only had the secondary weed and the second that had both the secondary weed and cheatgrass. These plots were controls to examine how the secondary weeds grew alone and in competition with cheatgrass. All seeding densities were 300 PLS m^{-2}.

The generalized timeline for all objectives of Experiment 2 was:

Experiment 2	2002		2003				2004				2005				2006			
	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall
Locate & prepare areas	X																	
Year 1 replicate																		
Herbicide appl.				X														
Seeding						X												
Measurements							X	X	X	X	X	X	X	X	X	X	X	X
Year 2 replicate																		
Herbicide appl.								X										
Seeding										X								
Measurements											X	X	X	X	X	X	X	X

Experiment 3: Restoration Strategies

The overall objective of Experiment 3 was to investigate the effectiveness of different restoration treatments. One of the restoration techniques (a spring herbicide treatment) was targeted at reducing the cheatgrass seed bank, and a second technique (the combination of an annual cover crop and a prescribed fire) was to tie up soil N and then reduce the cheatgrass seed bank. Our goals were: (1) by reducing the cheatgrass seed bank, reduce cheatgrass competition against the newly-seeded perennial species to provide a "window of opportunity" for establishment; and (2) by seeding an annual cover crop, tie up soil N so that cheatgrass competition was reduced against the newly seeded perennials. In addition, we used 2 seeding mixes in this experiment: the more competitive native species identified in Experiment 1 as well as the mix of species from Experiment 2 that differ in growth characteristics.

The overall experimental design for Experiment 3 is a split plot design. The main factor is a restoration strategy factor which consisted of four potential restoration choices:

- An unseeded control. In order to determine what happens when a land manager does nothing and lets the area recover naturally, we had a series of plots with no pre-treatment and no seeding.
- A seeded control. To provide a measure of how well the pre-restoration treatments improve establishment and growth of the desired perennial species, plots that had no pre-treatment but were seeded were also established.
- An herbicide treatment. Because herbicide restoration treatments have a high success rate in controlling cheatgrass before restoration, they serve as an experimental standard to judge the relative success of the other treatments. [Note: We are not specifically advocating the use of

herbicides (selection of a specific herbicide and dosage is beyond the scope of our studies), but as in the case of sugar applications, we recognize its utility in an experimental framework.]

- A prescribed seed-burn-seed treatment targeted to reduce both the cheatgrass seed bank and cheatgrass' access to available soil N. The seed-burn-seed treatment is a novel restoration strategy that is designed first to deplete available soil N with an annual cover crop, then to reduce the cheatgrass seed bank by a fall prescribed burn. The annual cover crop was one of the better sterile hybrids from Experiment 1 that was seeded in Fall 2004. The cover crop had 2 purposes: first to uptake soil N leaving less available to cheatgrass, and second to provide fine fuels to carry the prescribed burn. The prescribed burn was a low-intensity head fire to reduce the cheatgrass seed bank as well as to volatilize nitrogen. The second seeding was the final seed mix.

In addition to these four restoration treatments, two seed mixes were applied as a split plot factor: (1) the 6 accessions from the native plant screening trials (Experiment 1) that were found to be most competitive with cheatgrass and appropriate for the study site (and thus represents a transition community from cheatgrass to the desired community); and (2) the same seed mix used in the competitive interactions studies (Experiment 2).

Experiment 3 was conducted at one study area in NV. The four restoration treatments were applied in a randomized block design, with 3 blocks at the study area. Each block consists of 4 split-plots, with each whole plot receiving a different restoration treatment. The split-plot treatments were the 2 different seed mixes. Individual split-plots were relatively large (170 X 170 m) to provide better simulation of large-scale land treatments. Treatments within a block had a minimum 15 m (50') buffer area between them. Unlike Experiments 1 and 2, Experiment 3 was not be repeated in consecutive years.

The generalized timeline for Experiment 3 was:

Experiment 3	2002		2003				2004				2005				2006			
	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall
Locate & prepare areas						X												
Seed-Burn-Seed Treatment																		
Cover crop seeding										X								
Prescribed burn														X				
Herbicide treatment												X						
Final seeding (all treatments)														X				
Measurements														X	X	X	X	X

Integrated Initiatives

Several innovative approaches were used to promote awareness of invasive weed issues in the Great Basin for K-12 students, undergraduate students, and the general public:

- Aspects of invasive weed ecology and management, from the individual plant level to the ecosystem level, can be tied to K-12 core curricula (science, social studies, math, language arts). A traveling exhibit and classroom activity guide was developed to cover both the formal and informal education sectors, to increase learning through preparatory and follow-up activities, and to allow for free-choice learning. The traveling exhibit is appropriate for middle school and general public audiences and has eight panels that characterize impacts, plant characteristics, disturbance, ecological theory, management perspectives, research activities, community efforts, and personal involvement. The original concept and themes of the exhibit were developed by an undergraduate class, vetted at the 2005 Rangeland Ecology Workshop for Idaho Teachers, revised, and then vetted again.
- A second innovative approach was to develop an educational web site targeted for grades 6-16 as well as to supplement the traveling exhibit. As with the traveling exhibit, principles of instructional design have been followed during construction of the site, and free-choice learning paradigms were used. The web site offers in-depth information on the history and ecology of the Great Basin, biology and impacts of weedy plants, research activities, and management strategies.
- Undergraduate students at colleges and universities in or adjacent to the Great Basin participated in

research and management experiences associated with the program through a "Research Internship for Undergraduates" Program. Students interested in specific aspects of invasive weeds identified a faculty advisor and then developed a research project related to the on-going efforts. After students completed the project, they prepared a report and presented their findings.

Another major integrated initiative was to investigate the economic and social impacts of restoration in the Great Basin. Existing multi-period costs / profit optimization modeling techniques were used to investigate minimum economic costs of controlling cheatgrass on public rangelands and to contrast the restoration costs with the costs of no-action. To investigate societal attitudes about restoration, different stakeholder groups were interviewed to determine if the different groups had different concepts of restoration and how they perceived different restoration strategies and their associated costs.

Finally, results from this research were provided to agency personnel, public land managers, policy makers, and other interested individuals through traditional extension/outreach methods, including:

- Periodic field tours conducted at research sites to keep collaborating scientists, agency personnel, local officials, county agents, and interested land managers appraised of current research findings.
- Research findings presented at area and regional weed management seminars and workshops and at annual meetings and conferences of weed associations, land managers, and professional societies.

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Chapter 2 – Plant materials selections and seeding equipment modifications

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SPECIES SELECTION AND SEED PROCUREMENT

The cooperators of the IFAFS "Integrated Restoration Strategies Towards Weed Control on Western Rangelands" Project selected test species for studies based on seed availability of the most common species found in Wyoming big sagebrush plant communities throughout the Great Basin and Snake River Regions.

Experiment 1 – Plant Screening Trials involved replicated plot plantings using the Truax Rough Rider Rangeland Drill in fall of 2003 and 2004 at two locations in each of the states of Idaho, Nevada, Oregon and Utah (**Table 2.1**) to evaluate different releases for their competitive ability with cheatgrass. This experiment involved eight separate plantings each of the two years this experiment was planted. Seed for Experiment 1 was purchased from seed companies or supplied by NRCS, ARS, or the FS. At each location, 3 of 6 replications were treated with Roundup in late spring prior to planting and the other 3 replications were left untreated. Plots were 10 feet wide (one drill width) x 20 feet long. Species and accessions utilized in Experiment 1 are listed in **Table 2.2**. Additional details on the plot treatments and experimental design can be found in Chapter 5.

Table 2.1. Seeding dates for Experiment 1 at each study site.

State	Study site	2003 seeding dates	2004 seeding dates
Idaho	Canyon Creek	October 20-21	October 20-21
	Cinder Cone Butte	October 21-22	October 21-22
Nevada	Eden Valley	November 10-11	October 27-28
	Izzenhood Ranch	November 12-13	October 29-30
Oregon	Lincoln Bench	October 27-28	October 24-25
	Succor Creek	October 29-30	October 25-26
Utah	Simpson Springs	November 3-4	October 18-19
	Vernon Hills	November 5-6	October 17-18

Table 2.2. Species and accessions of plant materials used in Experiment 1 seedings.

Plant type	Latin name	Common name	Accession name	Sites seeded	Seed source	Seeding rate number PLS ft^{-1}	Seeding rate lbs PLS $acre^{-1}$
(1) Native perennial species	*Achillea millefolium*	Western yarrow	Eagle	All except: (1) NV-Izzenhood Ranch; (2) all ID & OR sites in 2004	Geertson Seed	50	0.5
	Achillea millefolium	Western yarrow	Great Northern	All except NV-Izzenhood Ranch	Bridger, MT PMC	50	0.5
	Achnatherum hymenoides	Indian ricegrass	Rimrock	Only NV-Izzenhood Ranch	Commercial	25	4.6
	Atriplex canescens	Fourwing saltbush	N/A	Only NV-Izzenhood Ranch	Local collection	25	21.0
	Atriplex confertifolia	Shadscale	N/A	Only NV-Izzenhood Ranch	Local collection	25	18.0
	Elymus multisetus	Big squirreltail	Sand Hollow	All	L&H Seed	25	5.7
	Elymus elymoides brevifolius	Bottlebrush squirreltail	Shaniko Plateau	All	L&H Seed	25	5.7
	Elymus lanceolatus lanceolatus	Thickspike wheatgrass	Bannock	All	Aberdeen, ID PMC	25	8.1
	Elymus lanceolatus lanceolatus	Thickspike wheatgrass	Critana	All	Bridger, MT PMC	25	8.1
	Elymus wawawaiensis	Snake River wheatgrass	Secar	All	L&H Seed	25	7.8
	Elymus wawawaiensis	Snake River wheatgrass	SERDP (KBJ)	All	ARS, Logan, UT	25	7.8
	Krascheninnikovia lanata	Winterfat	N/A	Only NV-Izzenhood Ranch	Local collection	25	8.9

Plant type	Latin name	Common name	Accession name	Sites seeded	Seed source	Seeding rate	
						number PLS ft^{-1}	lbs PLS acre^{-1}
	Leymus cinereus	Basin wildrye	Magnar	All except NV-Izzenhood Ranch	Aberdeen, ID PMC	25	8.4
	Leymus cinereus	Basin wildrye	Trailhead	All except NV-Izzenhood Ranch	Bridger, MT PMC	25	8.4
	Poa secunda secunda	Sandberg bluegrass	Hanford	All	L&H Seed	50	2.4
	Poa secunda secunda	Sandberg bluegrass	High Plains	All	Bridger, MT PMC	50	2.4
	Poa secunda secunda	Sandberg bluegrass	Mountain Home	All	Rainier Seed	50	2.4
	Poa secunda ampla	Sandberg bluegrass	Sherman	All	Pullman, WA PMC	50	2.4
	Pseudoroegneria spicata	Bluebunch wheatgrass	Anatone	All	SW Seed	25	7.8
	Pseudoroegneria spicata	Bluebunch wheatgrass	Columbia	All	Logan, UT ARS	25	7.8
	Pseudoroegneria spicata	Bluebunch wheatgrass	Goldar	All	Aberdeen, ID PMC	25	7.8
	Pseudoroegneria spicata	Bluebunch wheatgrass	P-7	All	Landmark Seed	25	7.8
	Sphaeralcea coccinea	Scarlet globemallow	UTDWR Source	All	UTDWR, Ephraim, UT	25	2.9
	Achnatherum thurberianum	Thurber's needlegrass	Orchard	Only Idaho and Oregon sites in 2004	USFS Shrub Lab, Boise, ID	25	4.8
(2) Comparison Standards	*Agropyron cristatum X desertorum*	Crested wheatgrass	CD-II	All	Aberdeen, ID PMC	25	6.6
	Agropyron fragile	Siberian wheatgrass	Vavilov	All	Aberdeen, ID PMC	25	6.8

Plant type	**Latin name**	**Common name**	**Accession name**	**Sites seeded**	**Seed source**	**Seeding rate**	
						number PLS ft^{-1}	**lbs PLS acre^{-1}**
(3) Hybrid Small Grains	*Triticum X Elytrigia*	Hybrid wheat	Regreen	All	Rainier Seed	25	91
	Triticum X Secale	Triticale	Pioneer	All	Granite Seed	25	91
		Triticale	Stani	All	Granite Seed	25	91
	Secale montanum	Mountain rye	Common	All	Stevenson Seed	25	60.5

Experiment 2 – Competitive Interactions Trials involved small replicated plots (1.5 x 2.5 meter) which were broadcast-seeded by hand in the fall of 2003 and of 2004 (**Table 2.3**). Seed for this Experiment was purchased from seed companies or supplied by NRCS, ARS, or the FS. Species and accessions utilized in Experiment 2 are listed in **Table 2.4**. Additional details on plot treatments, experimental design, seeding rates, and seed mixtures for Experiment 2 are discussed in Chapters 6 and 7.

Table 2.3. Seeding dates for Experiment 2 at each study site.

State	Study site	2003 seeding dates	2004 seeding dates
Idaho	Canyon Creek	November 18-20	November 17-19
	Cinder Cone Butte	November 18-20	November 17-19
Nevada	Eden Valley	October 26-27	November 1-2
	Izzenhood Ranch	October 28-29	November 3-4
Oregon	Lincoln Bench	November 20-22	November 15-17
	Succor Creek	November 20-22	November 15-17
Utah	Simpson Springs	November 1-15	November 1-15
	Vernon Hills	November 1-15	November 1-15

Table 2.4. Species and accessions of plant materials used in Experiment 2 seedings.

Plant type	Latin name	Common name	Accession name	Seed source	Site seeded
Native perennial species	*Achillea millefolium*	Western yarrow	Great Northern	Bridger, MT PMC	All
	Artemesia tridentata ssp. *wyomingensis*	Wyoming big sagebrush	N/A	Local collections for each site	All
	Elymus multisetus	Big squirreltail	Sand Hollow	L&H Seed	All
	Poa secunda secunda	Sandberg bluegrass	High Plains	Bridger, MT PMC	All
	Pseudoroegneria spicata	Bluebunch wheatgrass	Anatone	SW Seed	All
	Sphaeralcea coccinea	Scarlet globemallow	UTDWR Source	UTDWR, Ephraim, UT	All
	Agropyron fragile	Siberian wheatgrass	Vavilov	Aberdeen, ID PMC	All
Primary weed	*Bromus tectorum*	Cheatgrass	N/A	Local collections for each site	All
Secondary weed	*Centaurea virgata*	Squarrose knapweed	N/A	Local collections for each site	UT-Simpson Spring
	Lygodesmia juncea	Skeletonweed	N/A	Local collections for each site	ID-Cinder Cone Butte
	Taeniatherum caput-medusae	Medusahead	N/A	Local collections for each site	ID-Canyon Creek OR-Lincoln Bench

Experiment 3 – Restoration Strategies Trials involved the seeding of mixtures on large scale plots (approximately 10 acres each). Because of limited available funding, this experiment was conducted at only one site: Bedell Flats, located northeast of Reno NV. The site receives 8-10 inches mean annual precipitation and has sandy loam to loamy sand soils, 100-110 frost free days, and elevation of 4,500 – 5,500 feet. Approximately 150 acres were seeded. It was intended that the species that were most successful in Experiment 1 would be selected for use in Experiment 3. Three plots were seeded with a cover crop of winter triticale on October 30-31, 2004. The perennial seed mixes were planted November 3-8, 2005. Seed for this experiment were purchased from seed companies except as noted. Indian ricegrass was added to the mixture because Indian ricegrass was a natural species on the area being planted. Two seeding mixes were planted. Species and accessions for each mix utilized in Experiment 3 are listed in **Table 2.5**.

Table 2.5. Species and accessions of plant materials used in Experiment 3 seedings.

Seed mix	Latin name	Common name	Accession name	Seed source	Seeding rate (lbs PLS acre^{-1})
1	*Achnatherum hymenoides*	Indian ricegrass	Nezpar	Aberdeen, ID PMC	1.5
	Elymus elymoides brevifolius	Bottlebrush squirreltail	Shaniko Plateau	L&H Seed	0.6
	Elymus lanceolatus lanceolatus	Thickspike wheatgrass	Bannock	Cedera Seed	1.26
	Leymus cinereus	Basin wildrye	Magnar	Wind River Seed	1.05
	Poa secunda ssp. *ampla*	Sandberg bluegrass	Sherman	Wind River Seed	0.4
	Pseudoroegneria spicata	Bluebunch wheatgrass	Anatone	Wind River Seed	1.4
2	* *Achillea millefolium*	Western yarrow	Eagle	Geertson Seed	0.02
	* *Artemesia tridentata* ssp *wyomingensis*	Wyoming big sagebrush	N/A	Local collection	0.02
	Elymus multisetus	Big squirreltail	Sand Hollow	Cedera Seed	1.2
	Poa secunda secunda	Sandberg bluegrass	High Plains	Bridger, MT PMC	0.4
	Pseudoroegneria spicata	Bluebunch wheatgrass	Anatone	Wind River Seed	3.5
	Sphaeralcea coccinea	Scarlet globemallow	UTDWR Source	UTDWR, Ephraim, UT	0.1

NOTE: * Yarrow and sagebrush were broadcast seeded in alternate rows with Seed Mix #2

TRUAX DRILL MODIFICATIONS

The cooperators of the IFAFS "Integrating Weed Control and Restoration on Great Basin Rangelands" Project chose to use the Truax Rough Rider Rangeland Drill to seed Experiment 1 and Experiment 3 because the drill was considered the best available technology for rangeland seedings.

Personnel from the USDA-NRCS Aberdeen Plant Materials Center (PMC) were responsible for completing modifications to ensure both small (10 x 20 foot) plots in Experiment 1 and large (acreage size) plots in Experiment 3 would be planted accurately.

The Truax drill was delivered to the PMC in July 2003 so modifications to the drill could be completed. Due to safety issues identified by the manufacturer, the drill was recalled to the factory in mid-August. The drill was returned to the PMC in late September 2003. The following modifications were made prior to the first seeding project:

- Replaced accordion style drop tubes with smooth, clear tubes to facilitate seed flow from the seed box (**Photo 2.1**)
- Fabrication of V-shaped trough over individual seed cups to facilitate changing seed for each plot and cleanout between plots
- Mounted generator, vacuum cleaner and bag holder for changing seed between plots
- Mounted a handle on drive wheel for calibration and drill priming
- Modifications to facilitate calibration
- Removed agitator in cool season box to facilitate cleaning between plots
- Installed seats on drill platform
- Adjustment of press wheels to ensure accurate tracking behind openers

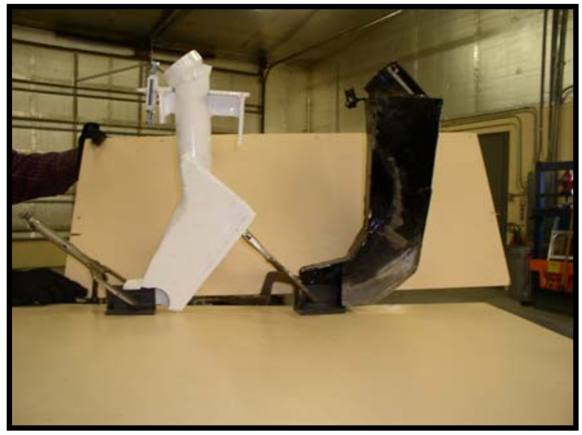

Photo 2.1. Re-designed seed drop tubes and boots (white boot) for a smoother flow of seed from the seed box to the soil.

On October 19, 2003 PMC personnel transported the drill to the Canyon Creek site in Idaho to begin seeding Experiment 1. Due to the time constraints imposed by the recall of the drill in August, PMC personnel did not have a chance to fully field test the drill under field conditions to determine how well the drill placed seed into the soil. It was assumed that the manufacturer had tested seed placement under rangeland conditions. Seeding began after delays in procuring the proper hitch and hydraulic connections between the drill and the tractor supplied by ARS.

Once seeding commenced, PMC personnel found seed bridging in the seed drop boot, drastically impeding seed flow to the soil. It was determined that the disk openers were not cutting a slot in the soil wide enough for seed to enter slot. The location where the seed left the boot was altered to direct more seed into the slot formed by the disk. Modifications to the drill while in the field were extremely limited due to lack of appropriate tools and materials. The Idaho sites (Canyon Creek and Cinder Cone Butte) were seeded under less than ideal conditions and much of the seed was not adequately covered with soil by the drill.

Photo 2.2. Wider disc opening in the soil for seed to drop into and press wheel adjustment to better cover seeds with soil behind disc openers.

The following week the Oregon sites were seeded. PMC personnel were able to make additional modifications prior to seeding. Seed tubes were extended past the boot re-directing where the seed dropped, which improved seed placement. Drag chains were also installed behind the press wheels to improve seed coverage. The Nevada and Utah sites were seeded following completion of the Oregon sites.

Prior to the seeding in the fall of 2004, the following additional modifications were completed:

- Wedges (from the manufacturer) were installed to adjust toe-in (7°) on disk openers (this widened the slot that the seed falls into) (**Photo 2.2**)
- Added flute adjustment crank wheel to improve adjustment of calibration (**Photo 2.3**)
- Constructed side load trailer ramps on 35 foot PMC trailer in order to haul both the drill and tractor (now supplied by PMC) with one truck
- Constructed hitch pin sleeve to use with clevis-type tractor drawbar to reduce the amount of play in pintle eye on drill
- Fabricated pintle hitch for tractor loader in order to side load drill with tractor

Photo 2.3. Addition of a crank wheel to improve accuracy and ease of calibration.

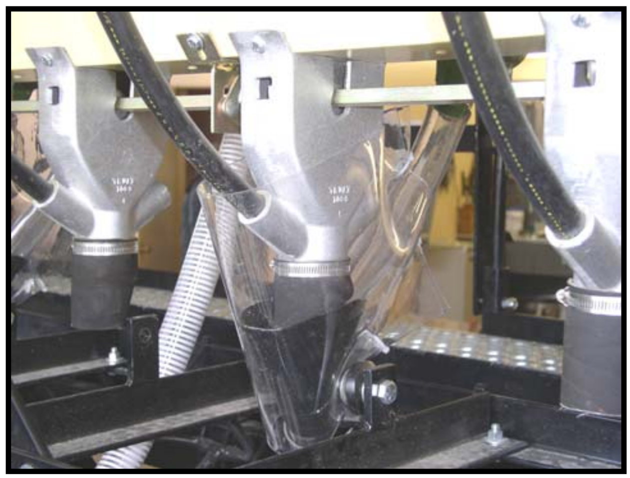

Photo 2.4. Addition of windshields to reduce seed loss during windy conditions.

The second year seeding of Experiment 1 plots were completed in late October and early November 2004. The ability to transport both the tractor and drill from site to site with one truck improved the efficiency of the project. A cover crop (triticale) was seeded on the Experiment 3 site in early November. The additional drill modifications significantly improved the seed placement and soil cover of the seed. The drill performed very well in maintaining seeding depth which was set at ½ to ¾ inch depth for the small grain cover crop.

In 2005, a new drill was used to seed Experiment 3. Many of the modifications that were made to the drill used the prior 2 years were installed on the new drill. Additional modifications included:

- Windshields added around seed cup drops to reduce seed loss during windy conditions (**Photo 2.4**)
- Broadcast seeders added to alternate rows

Photo 2.5. Addition of broadcast seeders to alternate rows of drilled and broadcast seeds to facilitate planting shallow-seeded species and deep-seeded species in a single operation.

to facilitate planting shallow seeded species as well as deeper seeded species in a single operation (**Photo 2.5**)

- Repositioned mounting brackets for broadcast seeders

This drill was used for the Crested Wheatgrass Diversification Project (Great Basin Native Plant Selection and Increase Project) and Experiment 3.

Mr. Jim Truax visited the seeding sites for the Crested Wheatgrass Diversification Projects in Utah and Oregon and was able to see how the drill performed with the modifications that had been made. After the first seeding project was completed in Utah, Mr. Truax manufactured new seed drop boots that were steeper, to improve seed drop. The new boots were installed on the drill and were used in Oregon (Crested Wheatgrass Diversification Project) and the seeding of Experiment 3 in Nevada.

Since completion of the seedings in 2005, Mr. Truax has manufactured a new seed drop boot that should further improve seed placement. The new boot will be installed and used in upcoming seeding projects. All of the modifications that have been made have incrementally improved the performance of the Truax Rough Rider Rangeland Drill. The Truax drill is a significant improvement over the older rangeland drills which had very poor control of seeding depth.

The cooperators of the IFAFS project thank Mr. Jim Truax for providing the drill for the project and his willingness to work with the project to make improvements to the drill. The excellent cooperation will undoubtedly pay great dividends in future rangeland seeding projects throughout the western United States.

Chapter 3 – Soil community dynamics in *Bromus tectorum*-invaded ecosystems of the northern Great Basin

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INTRODUCTION

Non-native invasive plant species potentially alter ecosystems by replacing native plant communities, varying the frequency or severity of disturbance regimes, altering above- and belowground food web dynamics, changing nutrient inputs and cycling, and potentially degrading economically important ecosystems (Chen and Stark 2000, Hilty et al. 2001). While much work has focused on aboveground components of invaded systems, little research has been done on changes affected on the soil biotic community, including soil microbes, invertebrates, and biological soil crusts (Belnap and Phillips 2001). Soil organisms play vital roles in executing ecosystem processes, and any changes in their abundance, activity or diversity should be understood in the context of broader landscape-level dynamics. Soil biotic communities respond to variability in resource quality and quantity, differences in rooting structures, and changes in soil nutrients, temperatures, and moisture that are directly or indirectly related to individual plant species. It is known that the biomass and composition of microbial communities differs in soils beneath different species of plants (Grayston et al. 1998, Bardgett et al. 1999, Kuske et al. 2002) and that exotic plant species have the potential to dramatically affect the microbial community (Kourtev et al. 2002).

The invasion of Bromus tectorum (cheatgrass) into former Artemisia tridentata (big sagebrush) steppe communities in the northern Great Basin has resulted in a loss of plant species richness and structural diversity, drastic changes in litter inputs, modification of the rhizosphere, and alteration of soil moisture and temperature regimes (Stewart and Hull 1949, Bolton et al. 1993). These relatively new soil conditions may have a measurable effect on the abundance, distribution, activity, and diversity of certain groups of soil organisms. Further, a simplified aboveground plant community may result in a simplified belowground community, and any loss in soil biological complexity has the potential to affect ecosystem functioning (Wall 1999). Processes such as decomposition, primary productivity, nitrogen fixation and nutrient cycling are dependent upon the activities of microbes and the organisms that graze upon them, such as protozoa, nematodes and microarthropods (Wall and Moore 1999). As more and more species are lost or displaced from the soil matrix, we may start to see pronounced changes in the functioning of these ecosystems. In addition, the disturbance of biological soil crusts by cattle grazing and subsequent annual weed invasion can result in the loss of an important source of nitrogen, as well as a loss of soil stability and changes in water infiltration rates (Belnap et al. 2001, Belnap 2002).

The aim of this study was to characterize changes in microbial biomass and community composition, soil nematode abundance and trophic structure, and biological soil crust cover and diversity in conjunction with restoration experiments taking place in eight sites across the northern Great Basin. We investigated soil microbiotic patterns at several spatial and temporal scales and asked whether those patterns could be best explained by landscape-level factors, management treatment effects, or individual plant species influences. Our work is the first comprehensive look at belowground community dynamics in cheatgrass-dominated areas of the Wyoming big sagebrush biome.

METHODS

Study Areas

Soil sampling and biological soil crust surveys were carried out for two different restoration experiments (described below) taking place at sites in eastern Oregon, southwestern Idaho, northern Utah, and northern Nevada. One low- and one high-precipitation (mean annual precipitation: 20-25 cm and 25-30 cm, respectively) site was located in each of the four states. Site selection was based on land ownership status (only BLM lands were used), ecological site description, mean annual precipitation, annual *B. tectorum* cover, soil type, slope, and rockiness. Both experiments began in October 2003 and were maintained and monitored until June 2005.

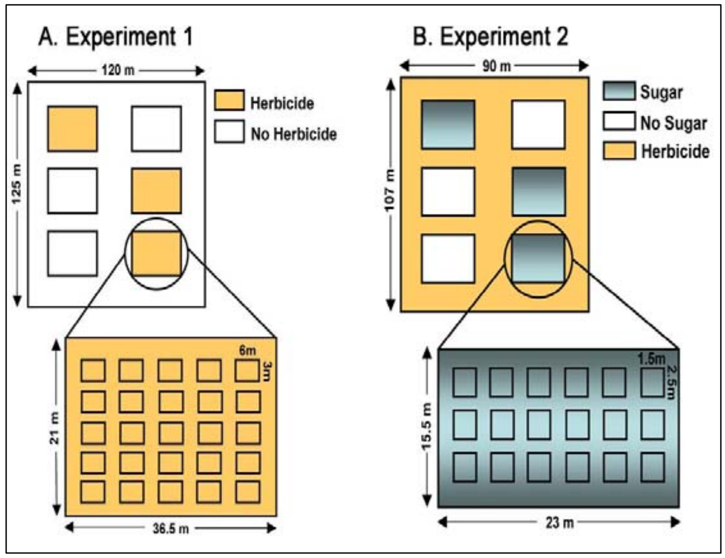

Fig 3.1. Plot designs for Experiments 1 and 2. (**A**) Experiment 1 plot configuration showing 6 plots (3 treated with herbicide, 3 untreated) at top and detail of 25 subplots at bottom. Each subplot was drill-seeded with a different plant accession to test its competitiveness with cheatgrass. (**B**) Experiment 2 plot configuration showing 6 plots (3 treated with sugar, 3 untreated) at top and detail of 18 subplots at bottom. Each subplot was hand-seeded with either a monoculture or mixture of six different native species, *B. tectorum*, and Vavilov Siberian wheatgrass to test how the depletion of soil resources affects competitive interactions between cheatgrass and native species.

Experiment 1: Native Plant Screening Trials

The objective of Experiment 1 was to assess the competitiveness of 25 different native plant accessions against cheatgrass. Most importantly, researchers wished to identify plant species that could be used as a transition stage, using the state and transition ecological model (Westoby et al 1989, Chambers 2000), from cheatgrass dominance to a sagebrush/bunchgrass plant community. At each site, 6 plots with 25 subplots each were established using a randomized split-plot design (**Fig. 3.1A**). Three of the plots were treated with herbicide to remove cheatgrass and provide a control reference. The other three plots remained untreated, and cheatgrass was allowed to grow and compete with the seeded varieties. In October 2003, the 25 plant accessions were seeded into the subplots using a low-impact Truax rangeland drill.

For all abiotic and biotic community analyses, soils were collected on four different sampling dates: March and May 2004, and March and May 2005. We collected soils from 14 of the 25 accession subplots (**Table 3.1**), focusing on species that are found in intact native sagebrush steppe communities. For the 2004 samplings, we pooled soils collected from accessions of the same species into a single sample. For example, we bulked two cores from each of the four Sandburg bluegrass accession subplots (for a total of eight cores) to be used as one Sandberg bluegrass sample. Because we saw little evidence for individual plant species effects on abiotic or biotic traits in 2004 (see Results below), for the 2005 samplings we categorized the seven plant species into three functional groups (native species, agricultural species, and unseeded) and sampled the soils accordingly.

Experiment 2: Competitive Interactions

The objective of Experiment 2 was to determine if the depletion of soil nitrogen and other soil resources affects the competitive interactions between cheatgrass and native species. Two techniques were used to deplete soil resources: 1) application of sugar to tie up soil N, and 2) a mix of native species that differed in growth form, rooting characteristics, and phenology. At each site, 6 plots with 18 subplots each were established in a randomized split-plot design (**Fig. 3.1B**). Three of the plots were treated with sugar and three were left untreated. The application of sugar to the soil surface promotes nitrogen immobilization by stimulating growth of the belowground microbial population, thereby making N unavailable to cheatgrass seedlings. Each subplot was then hand-seeded with either a monoculture or mixture of six different native species, *B. tectorum*, and Vavilov Siberian wheatgrass. We collected soils from 6 of the 18 subplots (**Table 3.2**), focusing on the native species mixes and their interactions with cheatgrass. Soils were collected on four separate sampling dates: March and May 2004, and March and May 2005.

Table 3.1. Experiment 1 plant species and accessions under which soil samples were collected for belowground community analyses.

Species code	Common name	Accession	Scientific name
03	Crested wheatgrass	CD-II	*Agropyron cristatum x desertorum*
05	Big squirreltail	Sand Hollow	*Elymus elymoides*
09	Snake River wheatgrass	Secar	*Elymus wawawaiensis*
10	Snake River wheatgrass	SERDP	*Elymus wawawaiensis*
11	Basin wildrye	Magnar	*Leymus cinereus*
12	Basin wildrye	Trailhead	*Leymus cinereus*
13	Sandberg bluegrass	Hanford Source	*Poa secunda*
14	Sandberg bluegrass	High Plains	*Poa secunda*
15	Sandberg bluegrass	Mountain Home	*Poa secunda*
16	Sandberg bluegrass	Sherman	*Poa secunda*
17	Bluebunch wheatgrass	Anatone	*Pseudoroegneria spicata*
18	Bluebunch wheatgrass	Goldar	*Pseudoroegneria spicata*
19	Bluebunch wheatgrass	P-12	*Pseudoroegneria spicata*
20	Bluebunch wheatgrass	P-7	*Pseudoroegneria spicata*
Unseeded	--	--	--

All soil samples were collected using a 2 cm diameter soil corer to a depth of 10-12 cm (approx. 400 g of soil). Soils were stored in coolers with icepacks, returned to the lab, and placed in a 4°C refrigerator. The following day, the soils were homogenized, passed through a 2 mm sieve, and processed for the analyses described below.

Table 3.2. Experiment 2 plant species monocultures and mixes under which soil samples were collected for belowground community analyses.

Species code	Common name(s)	Scientific name(s)
05	Cheatgrass	*Bromus tectorum*
06	Unseeded	--
09	Mix[a]	Mix
10	Mix + Cheatgrass	Mix + *B. tectorum*
17	Vavilov Siberian wheatgrass	*Agropyron spp.*
18	Vavilov Siberian wheatgrass + Cheatgrass	*Agropyron spp. + B. tectorum*

[a] 'Mix' refers to a mixture of 6 native species: Wyoming big sagebrush, High Plains bluegrass, Sand Hallow squirreltail, Anatone bluebunch wheatgrass, yarrow, and globe mallow.

Abiotic factors

Several abiotic soil factors were measured at all sites in both Experiments 1 and 2 throughout the course of the study to help account for soil community variability.

- <u>Soil moisture content</u> was measured at each of the four sampling dates and each sampled subplot by placing 20 g of soil in a drying oven at 105°C for 48 hours, weighing the dried soils, and calculating percent soil moisture.

- Soil matric potential was measured at each of the four sampling dates and each sampled subplot by placing one pre-weighed Whatman no. 42 filter (5 cm diameter) in between two other pieces of filter paper, and then placing all three filters in the soil sample for at least 24 hours (until the filter paper equilibrated with the surrounding soil). The middle filter was removed and weighed, and the resulting moisture content was calibrated against a moisture release curve to determine matric potential (Kaya and Stock 1997).
- Soil pH was measured in March 2004 and March 2005 for each sampled subplot by placing 10 g of soil in 20 mL of deionized water and stirring until mixed. The slurry was allowed to equilibrate with atmospheric CO_2 for 30 minutes and then stirred again. pH was determined to the nearest 0.1 unit using a Mettler-Toledo pH meter.
- Soil temperature was measured in March and May 2004 in Experiment 1 plots only using a portable soil thermometer.
- Soil stability was assessed using the slake test method prior to the beginning of the study. Soils were collected from a total of 18 samples per plot per site in Experiment 1 only. Stability was rated according to the time required for a small (~6 mm) ped to disintegrate during a 5-minute immersion. Soils were then categorized based on the proportion of soil fragment remaining after a set number of extraction-immersion cycles (**Table 3.3**). The higher the stability class, the more stable the soil surface.

Table 3.3. Soil stability class criteria for the slake test method.

Stability class	Criteria
0	Soil too unstable to sample
1	50% of structural integrity lost within 5 sec. of insertion in water
2	50% of structural integrity lost 5-30 sec. after insertion in water
3	50% of structural integrity lost 30-300 sec. after insertion in water or <10% of soil remains on sieve after 5 dipping cycles
4	10-25% of soil remaining on sieve after 5 dipping cycles
5	25-75% of soil remaining on sieve after 5 dipping cycles
6	75-100% of soil remaining on sieve after 5 dipping cycles

Microbial Community Analysis

Two methods were used to assess soil microbial community functioning, structure, and biomass. Community-level physiological profiling (CLPP) was performed using Biolog EcoPlates™ to qualitatively determine soil microbial functional diversity (Sinsabaugh et al. 1999). Phospholipid fatty-acid (PLFA) analysis, a culture-independent method, was performed to ascertain a fingerprint of the microbial community structure and biomass (Hill et al. 2000).

Community-level physiological profiles (CLPPs)

Soil microbial functional diversity was assessed using Biolog substrate utilization EcoPlates (Biolog Inc., Hayward, CA, USA). Each EcoPlate consists of a 96-well microtiter plate filled with 31 different carbon substrates and 1 water control, all replicated 3 times. Each well is also filled with tetrazolium violet dye that turns purple as the inoculated microbes respire and reduce the carbon source. Differences in well color development over five days represent the microbial community's ability to effectively use a particular substrate; the underlying assumption is that highly diverse microbial communities will utilize more of the substrates more completely (Sinsabaugh et al. 1999). This functional diversity cannot be correlated with taxonomic diversity, however, as more than one microbial taxon will generally be able to use each carbon substrate (Staddon et al. 1997).

Experiment 1. In March and May 2004, we collected soils from subplots seeded with the plant species listed in **Table 3.1**. In order to cut down on CLPP processing time and equipment costs, we pooled soil samples from the three herbicide and three non-herbicide plots for each of the seven plant species. Thus we processed 2 EcoPlates per plant species per site, for a total of 112 samples (7 plant species x 2 treatments x 8 sites) per 2004 sampling date.

In 2005, the seven plant species were categorized into three functional groups (native species, agricultural species, and unseeded), resulting in a reduced number of subplots to be sampled. Consequently, we were able to use one EcoPlate for each functional group per plot for a total of 144 samples (3 functional groups x 3 plots x 2 treatments x 8 sites) per 2005 sampling date.

Experiment 2. For all sampling dates, we collected soils from subplots seeded with each of the six species mixtures listed in **Table 3.2**. Similarly to Experiment 1, we pooled soil samples from the three sugar and three non-sugar plots for each species mixture. A total of 96 EcoPlate samples (6 species mixtures x 2 treatments x 8 sites) were processed per 2004 sampling date. Twelve additional soil samples were collected in 2005 from subplots seeded with the invasive grass, medusahead (*Taeniatherum caput-medusae*), at two high-precipitation sites (Canyon Creek, ID and Lincoln Bench, OR).

Laboratory procedure. 1 g of soil was placed in 99 mL phosphate buffer and placed in a refrigerator overnight. The following day the samples were shaken for 20 minutes at 160 rpm on a clinical rotator, resulting in a well-mixed soil slurry. For each sample, 100 μm of the slurry was pipetted under a laminar flow hood into an EcoPlate. Plates were incubated at room temperature and color development was determined using a PowerWave X 340 spectrophotometer at a wavelength of 596 nm. These values, which represent the microbial community's ability to utilize a particular substrate, were recorded at 24-hr intervals for 5 consecutive days (Sinsabaugh et al. 1999). The data used in this analysis are from the day 3 readings and have been standardized to the water control. The water column (all zeros) was removed and all resulting negative values were changed to zero.

Phospholipid fatty-acid (PLFA) analysis

Phospholipid fatty-acids (PLFAs) are found in the cell membranes of living microbes, and certain groups have "signature" lipids that serve as identifiers (Sinsabaugh et al. 1999). These signature lipids are used to create a taxonomic fingerprint of the microbial community, which includes gram+ and gram- bacteria, actinomycetes, fungi, and protozoa. PLFA analysis is also used to generate estimates of microbial biomass, relative taxa abundances, and fungal to bacterial ratios (REFS).

For Experiments 1 and 2, PLFA samples were processed for all plant species monocultures and mixtures listed in **Tables 3.1 and 3.2**, respectively. Unlike the CLPP analysis, we did not pool soils based on treatments, but rather kept samples from each of the six plots in both experiments separate. Therefore, for Experiment 1 there were a total of 336 (7 plant species x 3 plots x 2 treatments x 8 sites) and 144 (3 functional groups x 3 plots x 2 treatments x 8 sites) PLFA samples per sampling date in 2004 and 2005, respectively. For Experiment 2, the totals were 288 (6 species mixtures x 3 plots x 2 treatments x 8 sites) and 324 (36 additional samples from medusahead subplots) per sampling date in 2004 and 2005, respectively.

After sieving the soils, 10-14 g subsamples were weighed, freeze-dried and stored in a 0°C freezer in vacuum-sealed packages in sealed containers until further processing could be completed. We extracted lipids from the soils using a modified PLFA/fatty-acid methyl ester (FAME) technique (T. Balser, University of Wisconsin-Madison). Samples were homogenized using a mortar and pestle and 4 g subsamples were weighed into Teflon test tubes. Chloroform was added to each soil sample, causing the microbial cells to lyse. Lipids were then isolated from the cell membrane through a series of cleansing and extracting phases. The resulting collection of dried lipids was resuspended in a hexane and MTBE solution before being analyzed on a gas chromatograph with a flame ionization detector (GC/FID). The GC/FID heats the organic compounds and separates them based on their volatility. The compounds are then blasted with electrons and broken into ions in the mass spectrometer (MS); the MS generates counts of ions with each specific mass. The resulting data are graphed to produce a mass spectrum for the sample, where each peak represents a different lipid. The chromatogram is lined up with known bacterial and fungal markers, thereby creating a fingerprint of the biotic community in the soil.

Soil nematodes

Soil nematodes occupy important positions as primary and secondary consumers in belowground food webs (Bongers and Ferris 1999), have well-documented effects on nutrient cycling dynamics and plant community structure (Yeates 1979, Wardle et al. 2004), and can be used as bioindicators of soil ecosystem status (Bongers 1990, Bongers and Ferris 1999, Porazinska et al. 1999). We were interested in how nematode communities would respond to the restoration management schemes implemented in this study.

For both Experiments 1 and 2, nematode samples were processed for all plant species monocultures and mixtures listed in **Tables 3.1 and 3.2,** respectively. Total numbers of nematode samples were the same as the PLFA samples listed above. Soil nematodes were extracted using the sugar centrifugation technique (Kaya and Stock 1997). This method separates live and dead adults, juveniles, and eggs from the soil matrix using a series of sieves in conjunction with density-dependent flotation. A subsample of 100 g of soil was mixed in 800 mL of water and stirred in a figure-8 pattern for 30 seconds to 1 minute. The mixture was allowed to settle for 1 minute, after which time it was poured over two stacked sieves with 250 μm and 38 μm openings. The silt and nematodes remaining on the bottom sieve were gently poured into a 50 mL centrifuge tube. Samples were then centrifuged at 3000 rpm for 3 minutes; this step produces a soil pellet containing all the nematodes at the bottom of the tube. After pouring off half of the water, the tube was filled with a 1M sucrose solution and centrifuged again at 3000 rpm for 3 minutes. During this step, the "light" nematodes remain suspended in the sucrose solution while the "heavy" soil is forced to the bottom of the centrifuge tube. The nematodes were then poured onto a small sieve, rinsed thoroughly with tap water, and transferred to a glass vial. The samples were refrigerated at 4°C until further processing could be completed.

Nematode counts and trophic group identifications were performed on a Leica inverted interference contrast compound microscope. Samples were poured into a counting dish with 16 full squares and 16 partial squares; generally half of the dish was counted and identified, but when the nematodes were very dense, as little as 1/6 of the dish was read. Nematodes were categorized into one of the following six trophic groups based on their feeding structures: bacterial feeders, fungal feeders, root associates, plant parasites, omnivores, and predators (Porazinska et al. 2003). Thus far, only the 2004 nematode samples have been processed due to time and personnel constraints.

Biological soil crusts

Biological soil crusts are conglomerations of bacteria, fungi, cyanobacteria, lichens, mosses, and liverworts that have important ecological functions in arid and semi-arid ecosystems (Belnap et al. 2001). Soils in these ecosystems tend to be medium- to coarse-textured and lack the large accumulations of organic matter that stabilize soils in more productive ecosystems. Biological soil crusts, with their dense networks of cyanobacterial filaments and fungal hyphae, are excellent at preventing soil erosion from the interspaces of sagebrush and bunchgrass communities (Rosentreter and Eldridge 2003). Biological soil crusts are also an important source of nitrogen in these otherwise N-limited systems because of the presence of free-living and lichen-associated nitrogen-fixing cyanobacteria (Belnap et al. 2001).

We were interested in how the biological soil crust communities differed between the eight sites in this study and how those differences might relate to the results found in the native plant screening trials (Experiment 1). Secondarily, we wished to examine the effects of the minimum-impact rangeland drill used in Experiment 1 on the crusts at each site.

Biological soil crust surveys for all sites were conducted on three separate occasions. The first survey occurred in October 2003, before the rangeland drill had seeded the Experiment 1 plots. The second survey was conducted in March 2004, and the final survey occurred in March 2005. In each plot, we established 2 15 m transects (at Cinder Cone Butte, ID we ran 3 transects per plot due to the high crust cover) (**Fig. 3.2, left photo**). Each plot also had two control transects placed just outside the boundaries of the plot area. We used the line-point intercept method with a 25 x 25 cm quadrat frame to assess crust cover and type. A nail was placed in the ground every 2 meters (at 0, 2, 4, 6, 8, 10, 12 and 14 m), and the quadrat was placed on the right side of the measuring tape with the lower right corner hugging the nail (**Fig. 3.2, right photo**). A pinflag was dropped in the lower left corner of each of 20 grid points in the quadrat (except for the last column, in which the pinflag was positioned flush against the PVC edge of the frame). We recorded the class cover and specific information about the biological soil crust organism if one was present. In the case of physical (vesicular) crusts we also measured the shear strength, which was measured with a Torvane shear meter. Class cover was recorded as bare ground, cyanobacteria, lichen, moss, cow patty, physical crust, rock, litter, or vascular plant.

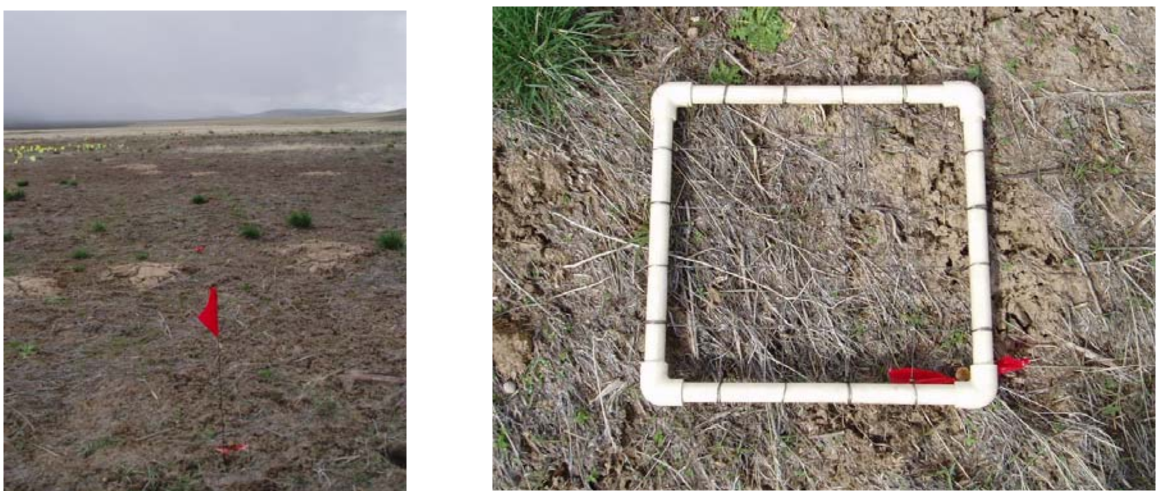

Fig. 3.2. Biological crust survey transect (left) and sampling quadrat (right).

Statistical Analyses

Multivariate statistical analyses on biological community data were performed using PC-Ord version 5.11 beta (McCune and Mefford 1999). Biolog EcoPlate spectrophotometer data were analyzed using principal components analysis (PCA), where samples were ordinated in carbon substrate space. PCA was deemed an appropriate analysis because the data had very low heterogeneity and substrates appeared to be linearly interrelated by examination of scatterplot matrices. The cross-products matrix contained correlation coefficients among substrates. Significance of principal components was determined by comparing the eigenvalues to the eigenvalues of a broken-stick model (Jackson 1993).

Nonparametric multidimensional scaling (NMS) with the Sørensen distance measure was used to assess PLFA community structure and nematode trophic group patterns at the site, treatment, and plant species levels. NMS is an iterative ordination technique that attempts to find a stable solution with minimum stress, or departure from monotonicity, in the reduced ordination space. It is well-suited to ecological data because it avoids assumptions of linearity and normality (McCune and Grace 2002). The medium setting of 'autopilot' was used with random starting configurations and 50 runs with real data. Monte Carlo randomization tests were performed against real data to evaluate the significance of the *k*-dimensional solution.

Outliers were identified as sample units with an average distance greater than 2.5 standard deviations from the mean that exhibited undue influence on the ordination results; these were deleted from the dataset. Statistical significance and strength of *a priori* within-in group membership were tested using one-way multi-response permutation procedures (MRPP), which provides a *p*-value and effect size, *A*, that is independent of the sample size. For outlier analysis and MRPP, Euclidean distance was used for the Biolog dataset and Sørensen distance was used for the PLFA and nematode datasets.

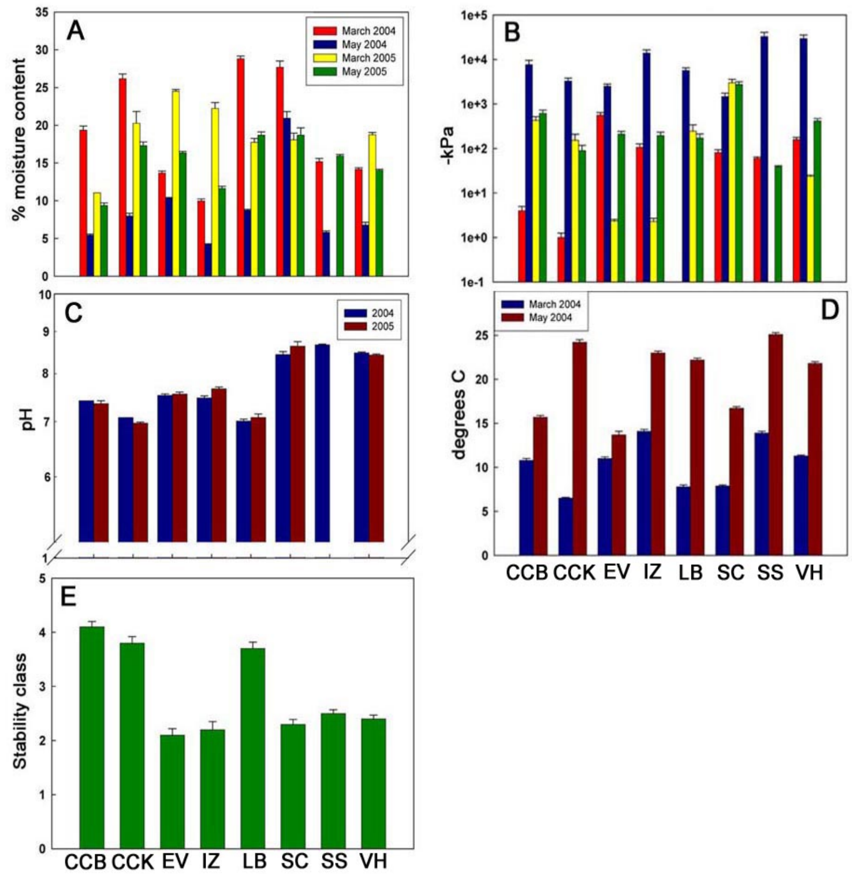

Fig. 3.3. Abiotic factors measured in IFAFS Experiment 1 for all eight sites (mean + SE). (**A**) Gravimetric soil moisture content, measured for all four sampling dates. (**B**) Soil water potential, measured for all four sampling dates (see legend A). (**C**) Soil pH, measured in March 2004 and March 2005. (**D**) Soil temperature, measured in March and May 2004. (**E**) Soil stability class, measured using the slake test method in April 2004 (CCB, CCK, LB, SC), June 2004 (SS, VH), and July 2004 (EV, IZ). CCB = Cinder Cone Butte, ID; CCK = Canyon Creek, ID; EV = Eden Valley, NV; IZ = Izzenhood Ranch, NV; LB = Lincoln Bench, OR; SC = Succor Creek, OR; SS = Simpson Springs, UT; VH = Vernon Hills, UT. Samples were not collected from Simpson Springs, UT, in March 2005.

RESULTS

Abiotic Factors

Abiotic soil factors varied among sites in both Experiments 1 and 2 (**Figs. 3.3 & 3.4**). Percent soil moisture content was always higher in March than in May, with the Idaho and Oregon sites having the highest soil moisture in March 2004 and the Nevada and Utah sites with the highest moisture in March 2005 (**Figs. 3.3A and 3.4A**). Matric potential, which represents the soil water available to plants and soil organisms, was most negative in May 2004 for all sites except Succor Creek, OR (**Figs. 3.3B and 3.4B**). There were large differences in pH between sites, ranging from 7.01 at Lincoln Bench, OR (high precipitation site with high percentage of litter and organic matter) to 8.67 at Simpson Springs, UT (low precipitation site with high percentage of bare ground and little organic matter) (**Figs. 3.3C and 3.4C**). Soil temperature was recorded for Experiment 1 plots in 2004 and found to be significantly higher in May than March (**Fig. 3.3D**). Soil stability class, measured for Experiment 1 only, was found to be highest at the two Idaho sites and the high precipitation Oregon site (Lincoln Bench) (**Fig. 3.3E**).

Community-Level Physiological Profiles (CLPPs)

Principal components analysis revealed CLPPs to be strongly patterned by site in both Experiments 1 and 2 (**Fig. 3.5**; Experiment 1 ordinations and statistics shown only). Patterns were similar in March and May 2004, with highly significant effect sizes at the site level (**Table 3.4**). Treatment and plant species effects were not significantly different when all sites were analyzed together (**Fig. 3.5B and 3.5D; Table 3.4**). Soil samples from sites with the highest mean pH values (Simpson Springs, UT, Vernon Hills, UT, and Succor Creek, OR) tended to cluster together in all CLPP analyses.

Phospholipid Fatty-Acid Analysis

PLFA analyses have been completed for the 2004 Cinder Cone Butte, ID, and Simpson Springs, UT, samples. Both sites are classified as low precipitation sites, but they have very different mean pH values (CCB = 7.42, SS = 8.67), soil surface components (CCB = lichen cover, SS = bare ground; see results below) and vegetative cover. In Experiment 2, soil community composition was strongly patterned by treatment (sugar vs. no sugar) and site (**Fig. 3.6**), and this result was consistent over time. The most surprising result was the strong correlation between abundance of the fungal PLFA biomarker with the sugar treatment at both sites. Fast-growing zygomycetes may be principally responsible for the increase in fungal growth, but morphological or genetic work will need to be done to confirm what specific group or groups are responding.

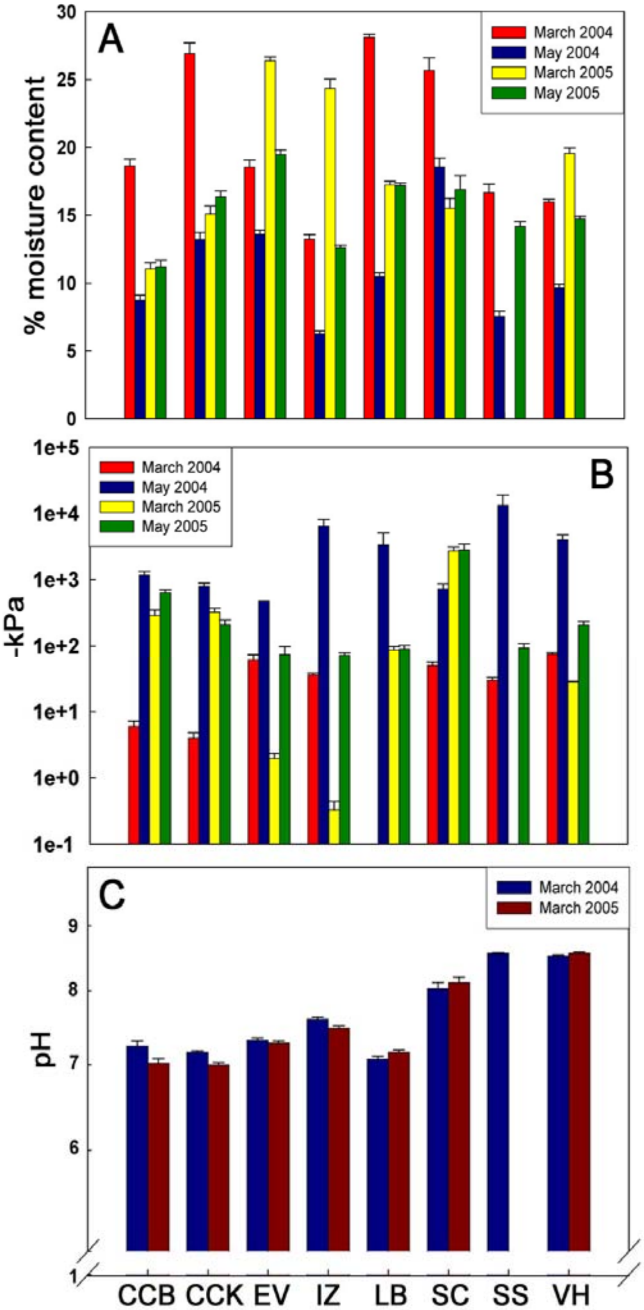

Fig. 3.4. Abiotic factors measured in IFAFS Experiment 2 for all eight sites (mean + SE). (**A**) Gravimetric soil moisture content, measured for all four sampling dates. (**B**) Soil water potential, measured for all four sampling dates. (**C)** Soil pH, measured in March 2004 and March 2005. CCB = Cinder Cone Butte, ID; CCK = Canyon Creek, ID; EV = Eden Valley, NV; IZ = Izzenhood Ranch, NV; LB = Lincoln Bench, OR; SC = Succor Creek, OR; SS = Simpson Springs, UT; VH = Vernon Hills, UT. Soils were not collected from Simpson Springs, UT in March 2005.

Table 3.4. Multi-response permutation procedures (MRPP) results for community-level physiological profiles, Experiment 1. ***A** is a measure of the effect size and is independent of sample size.

Date	Comparison	A*	*p*-value
March 2004	Site	0.203	0.000
March 2004	Treatment	0.004	0.096
March 2004	Plant species	-0.017	0.999
May 2004	Site	0.210	0.000
May 2004	Treatment	-0.001	0.429
May 2004	Plant species	-0.008	0.786

Soil Nematodes

Total soil nematode numbers were higher in May than in March 2004, with the highest number of nematodes recovered from Cinder Cone Butte, ID from Experiment 1 plots in May 2004 (**Fig. 3.7**). A treatment difference (herbicide vs. no herbicide) was found only at Canyon Creek, ID, in May 2004.

Similar to the CLPPs, nematode trophic group structure was strongly patterned at the site level (**Fig. 3.8**), but we found no effects at the treatment or plant species levels for either Experiments 1 or 2

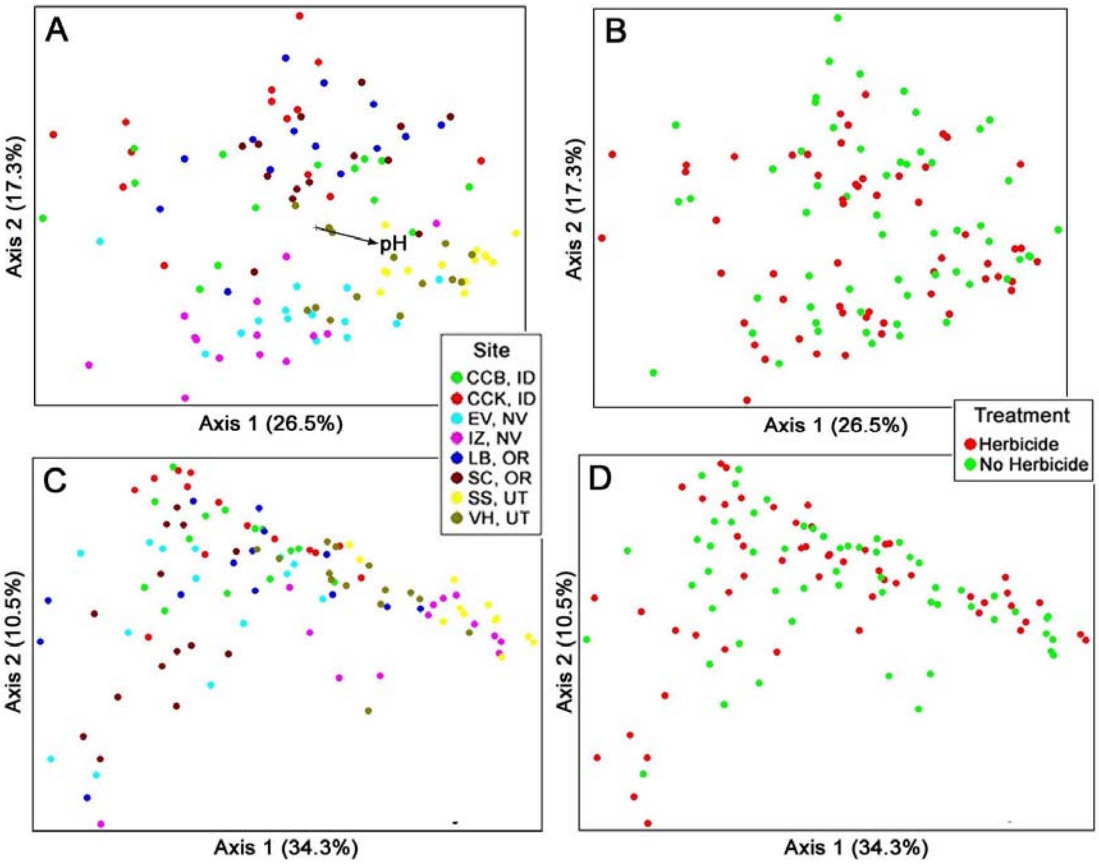

Fig. 3.5. Principal components analysis (PCA) of Biolog EcoPlate samples ordinated in carbon substrate space, Experiment 1, March and May 2004. Percent variance explained for axes 1 and 2 appear in parentheses. **A**. Sample units color-coded by site for March 2004. Vector represents the direction and magnitude of correlation between sample units and pH gradient. **B**. The same ordination as shown in A; sample units are color-coded by treatment. **C**. Sample units color-coded by site for May 2004. **D**. The same ordination as shown in C; sample units color-coded by treatment. CCB = Cinder Cone Butte, ID; CCK = Canyon Creek, ID; EV = Eden Valley; IZ = Izzenhood Ranch, NV; SC = Succor Creek, OR; SS = Simpson Springs, UT; VH = Vernon Hills, UT.

when all sites were analyzed together (ordinations not shown). Nematode trophic group samples also clustered by soil surface cover when sites were qualitatively assigned to cover classes as determined by our crust surveys (**Fig. 3.9**; see survey results below). As in the CLPP analysis, the three sites with the highest mean soil pH values (Simpson Springs, UT, Vernon Hills, UT, and Succor Creek, OR) tended to cluster together in the NMS ordinations, and bacterial feeding nematodes were always most abundant in these sites (**Figs. 3.8 and 3.9**). Root associates were more common at the Idaho sites (Canyon Creek and Cinder Cone Butte) in March 2004, while fungal feeders were abundant at Izzenhood Ranch, NV, in May 2004 (**Fig. 3.8 and 3.9**).

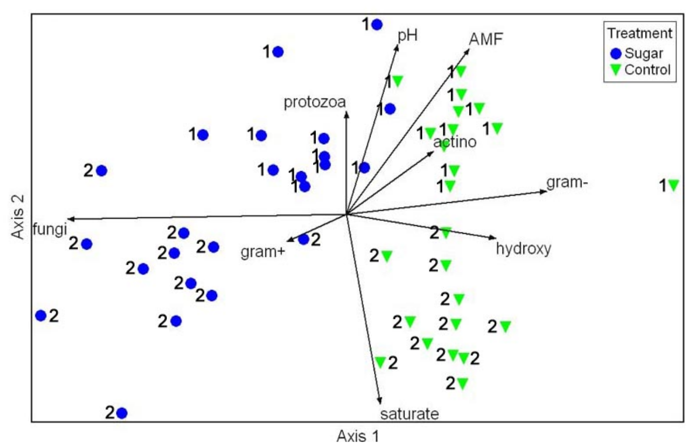

Fig. 3.6. Non-parametric multi-dimensional scaling (NMS) ordination of soil samples collected from Simpson Springs, UT (1) and Cinder Cone Butte, ID (2) for Experiment 2 in March 2004 and analyzed for soil community composition as determined by phospholipid fatty-acid analysis. Vectors represent the direction and magnitude of correlation between sample units and microbial taxa and pH.

Biological Soil Crusts

We found strong differences in biological soil crust cover between sites (**Fig. 3.10**). Cinder Cone Butte, ID, was the only site found to have a high percentage of lichen cover, while Izzenhood Ranch, NV,

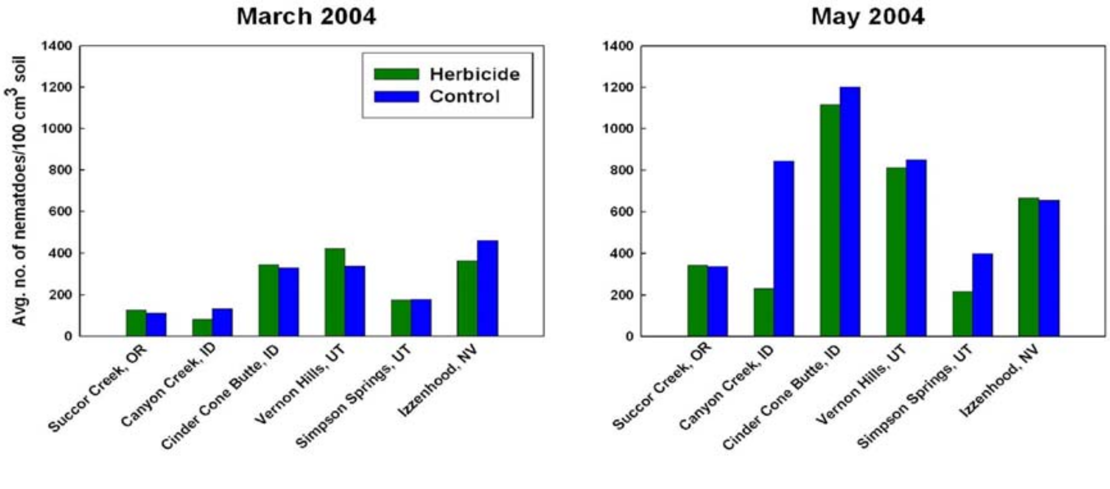

Fig. 3.7. Mean number of soil nematodes per site for Experiment 1, March and May 2004.

was highest in cyanobacterial crust cover. A thick cheatgrass thatch layer dominated Canyon Creek, ID, and Lincoln Bench, OR, both high precipitation sites. Succor Creek, OR, Simpson Springs, UT, and Vernon Hills, UT, tended to have high percentages of physical crust and bare ground.

DISCUSSION

Soil community composition varies due to a myriad of factors at play in the soil environment. Soil forming factors, such as climate, topography, parent material, vegetation, and time play important roles at the landscape level, while local weather patterns, soil texture and aggregate structure, rhizosphere effects, soil nutrient and chemical status, and belowground food web dynamics work to create amazingly heterogeneous habitats at the microscale level. We were interested in characterizing soil community composition at both of these levels in conjunction with sagebrush steppe restoration experiments across the northern Great Basin. We found that soil communities were strongly patterned by site differences, and that those differences could be best explained by soil pH and surface cover type. pH is an indirect and integrative measure of, among other things, precipitation, soil organic matter formation and decomposition, cation exchange capacity, nutrient status, and microorganism activity. Therefore it is not surprising that pH emerged as an important abiotic factor in structuring microbial and nematode community patterns in these arid ecosystems.

Treatment effects were not detectable when all sites were analyzed together, but we did see some effects of the sugar treatment (Experiment 2) on microbial community structure when sites were examined individually (**Fig. 3.6**). Sugar applications

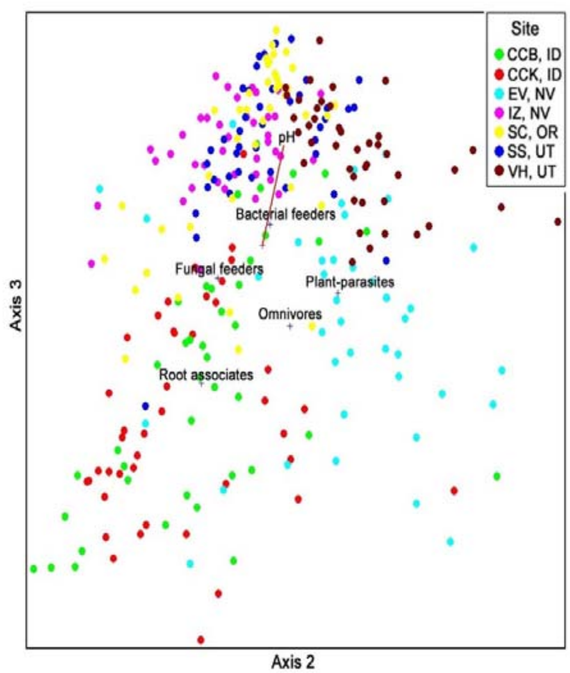

Fig. 3.8. NMS ordination of soil samples taken from Experiment 1 plots in March 2004 and analyzed for nematode trophic group composition. Axes 2 and 3 of a 3-dimensional solution shown. pH vector represents the direction and magnitude of correlation between the sample units and pH gradient. Nematode trophic group labels indicate the central tendency of each trophic group. CCB = Cinder Cone Butte, ID; CCK = Canyon Creek, ID; EV = Eden Valley; IZ = Izzenhood Ranch, NV; SC = Succor Creek, OR; SS = Simpson Springs, UT; VH = Vernon Hills, UT. Nematodes were not extracted from Lincoln Bench, OR, in March 2004.

tend to stimulate opportunistic members of the soil community by providing a high-energy and easily-degradable carbon source, therefore we would expect the community structure to change considerably. However, it is difficult to predict the magnitude of change, especially in arid ecosystems, and the duration of the effect, given the dynamic nature of microbial populations. Our initial analysis of the PLFA biomarkers indicates that the magnitude of change is indeed large and can last at least throughout the growing season. This is significant in light of other work showing that fungal abundance decreases when the dominant plant species changes from sagebrush to cheatgrass (N. DeCrappeo, unpublished data). As a restoration tool, applying sugar may have the added benefit of not just limiting the nitrogen supply for cheatgrass, but helping to re-establish the fungal component of the soil ecosystem. However, it is important to note that we have not yet assessed the specific fungal groups being gained or lost in these systems, so this speculation must be taken with a grain of sugar… or rather, salt.

We saw no plant species effects on microbial or nematode community patterns at any of the sites. In spring 2004, the plants were still very small and rhizosphere effects were probably negligible. We are continuing to analyze the 2005 data to determine if individual plant species, especially native species compared to agricultural species, produce a discernible change in the belowground community structure and functional diversity.

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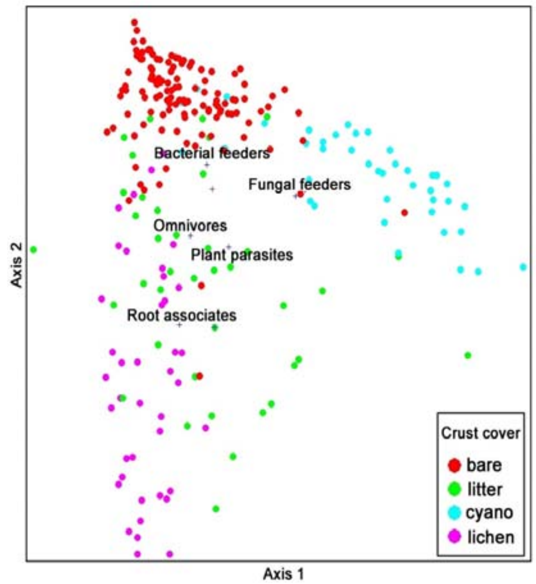

Fig. 3.9. NMS ordination of soil samples collected from Experiment 1 plots in May 2004 and analyzed for nematode trophic group composition. Samples are grouped by biological soil crust cover type. Axes 1 and 2 of a 3-dimensional solution are shown. Nematode trophic group labels indicate the central tendency of each trophic group. Bare = bare ground (i.e., loose soil); Litter = plant litter or thatch; Cyano = cyanobacterial crust cover; Lichen = lichen

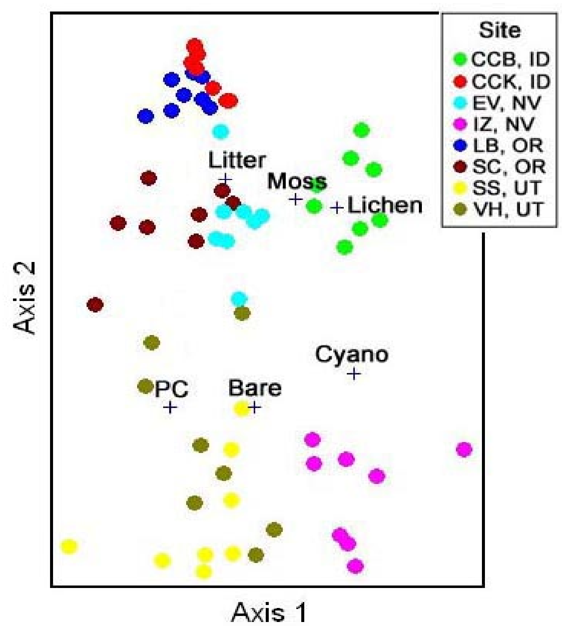

Fig. 3.10. NMS ordination of biological soil crust surveys performed at sites across the northern Great Basin. Axes 1 and 2 are shown from a 3-dimensional solution. Crust class label positions indicate the central tendency of each class type. CCB = Cinder Cone Butte, ID; CCK = Canyon Creek, ID; EV = Eden Valley; IZ = Izzenhood Ranch, NV; SC = Succor Creek, OR; SS = Simpson Springs, UT; VH = Vernon Hills, UT; Bare = bare ground (i.e., loose soil); Cyano = cyanobacterial crust; PC = physical crust.

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Chapter 4 – Soil Chemical and Physical Properties

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Part I: Soil Morphology and Paired Site Comparisons

INTRODUCTION

The type of vegetation covering the soil surface influences development of soil structure, which regulates air and water movement into and through the soil and rates of microbial decomposition (Angers and Caron, 1998). Cheatgrass (*Bromus tectorum* L.) invasion has been shown to change the composition and quantity of burrowing fauna, root pores, root exudates, mycorrhizal associations, and assemblages of microbial species (Belnap and Phillips, 2001; Kuske et al., 2002), each of which contribute to soil structure (Birkeland, 1984) and the rate of soil organic matter (SOM) decomposition. Cheatgrass invasion also changes the timing, distribution, and composition of organic matter inputs, as well as uptake of mineralized nutrients (Rickard, 1985; Bolton et al., 1990; Evans et al., 2001). Such shifts in SOM input and uptake may fundamentally alter partitioning of SOM among active, slow, and passive pools, which are thought to exert important influences on ecosystem structure and function (Parton et al., 1987; Gill and Burke, 1999).

The objective of our study was to evaluate changes in soil morphology and the distribution and composition of SOM associated with cheatgrass invasion of sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & A.W. Young) steppe communities. Our intention was to compare soils beneath near monocultures of annual grass at the IFAFS research plots to those beneath nearby sagebrush-dominated vegetation. Our underlying hypothesis was that soils under cheatgrass-dominated vegetation exhibit morphological characteristics and organic matter dynamics that facilitate depletion of slow and passive SOM that turns over on the order of decades to centuries and enrichment of active SOM that turns over at least once per year.

MATERIALS AND METHODS

Soil morphology and SOM dynamics were compared in soil profiles beneath annual grass-dominated research plots and nearby big sagebrush-dominated vegetation matched as well as possible with respect to parent material, landscape position, and other soil development factors

Field Procedures

One soil pit in annual grass vegetation (nearly 100% cheatgrass or medusahead [*Taeniatherum caput-medusae* (L.) Nevski] cover) at each site was located within the fenced research plot but away from the replicated restoration treatments. One soil pit in sagebrush-dominated vegetation (largely uninvaded by weedy annual grasses) at each site was located with pit walls beneath grass and shrubs representative for the site and as near as possible to the research plot. Soil profiles were described and sampled as per procedures developed by the USDA Natural Resources Conservation Service (NRCS, 1993) in soil pits measuring 1 m wide by 2 m long by 1 m deep (or to bedrock) that were excavated by hand. Horizon depths, colors, root size and density, and other morphological features were described beneath grass-interspace portions of the soil pits. One bulk soil sample was collected from three of the pit walls for each soil horizon to reflect the shrub-grass-interspace composition of the site. We used a standard bucket auger to excavate and sample soil horizons to 2 m or as deep as possible from the bottom of the soil pit.

Replicated samples were collected from two depths (0 to 10 cm and 10 to 20 cm) at five random bearings (0 to 360 degrees) and distances (1 to 25 m) from each soil pit (**Fig. 4.1**). Two distinct locations were sampled in the native half of each pair: 1) adjacent to the nearest grass plants and 2) beneath the nearest shrub canopy.

Vegetation at each site was evaluated for areal cover (Daubenmire, 1968) at 0.25-m x 0.25-m square quadrats at the soil sampling locations. Litter samples were collected from 15-cm x 15-cm square plots directly over soil sampling locations. The location of each sampling point was recorded with a Trimble GeoXM GPS unit.

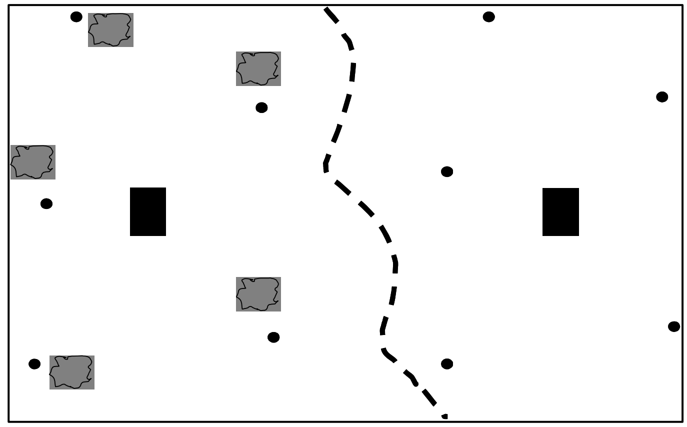

Fig. 4.1. Schematic layout of study design. Black rectangles denote soil pits and dots represent sample collection points for vegetation cover, litter, and 0- to 10- and 10- to 20-cm soil samples.

Laboratory Procedures

Air-dry samples were analyzed for carbon (C), nitrogen (N), phosphorus (P), nitrate N (NO_3-N), ammonium N (NH_4-N), potentially mineralizable N (PMN), phosphate, potassium (K), iron (Fe), manganese (Mn), inorganic C ($CaCO_3$), pH, bulk density, and particle-size distribution in soil laboratories of the University of California Division of Agriculture and Natural Resources, Davis, CA, and the USDA-ARS Exotic and Invasive Weeds Research Unit, Reno, NV. Litter composition, including C, N, lignin, and lignin-N, was analyzed at the UC-DANR laboratory in Davis.

Data from upper soil horizons were analyzed by paired difference t-test (Steel & Torrie, 1980). Data from replicated soil samples were analyzed by ANOVA with least significant differences noted at the $P<0.05$ level (SPSS, Chicago, IL).

RESULTS AND DISCUSSION

Preliminary analyses of data show distinct differences in soil organic matter and nutrient dynamics, many of which appear to be the result of plant community differences. **Table 4.1 s**ummarizes cover data and shows that vegetation cover on the annual grass sites is dominated by dense cheatgrass cover with little bare soil, with the exception of the Canyon Creek site, which is dominated by medusahead, and the Izzenhood Ranch site, which has a significant component of *Poa secunda*. Sagebrush interspaces all had appreciable bare soils and native herbaceous cover with from zero to 25 percent annual grass. Samples from beneath big sagebrush canopies have little bare soil because of appreciable litter cover. Cheatgrass ranges from one to 34 percent in the sub-canopy sampling locations.

Composition of plant litter at the paired sites (**Table 4.2**) shows annual-grass litter to be higher in both C and N than that of sagebrush and sage interspaces, but generally lower in lignin, though this is inconsistent across the sites. This suggests that annual grass litter may decompose more rapidly and completely, contributing less to long-term SOM pools.

Comparison of soil morphological characteristics for the top three horizons across sites (**Table 4.3**) shows that sagebrush A horizons are consistently slightly thicker than those under annual grasses. They range from one to five cm thicker at five of the sites, equal at two sites, and the annual grass A horizon is one cm thicker at one site (**Table 4.4**). Bulk density was not significantly different averaged across the six sites where we were able to measure it in A horizons, but it was lower at three in the annual grass A horizons, higher in one, and equal to sagebrush A horizons at two of the sites. A previous study comparing soils beneath high ecological condition native shrub steppe and cheatgrass-dominated vegetation found significantly thinner and less dense A horizons in the cheatgrass dominated soils (Norton et al., 2004). The authors attributed this to plant functional differences that lead to more above-ground allocation of organic matter by cheatgrass. Lower bulk density is likely a result of the high density of very fine roots in near-surface soils. These roots die each season and leave many fine tubular pores. We observed this difference in size and occurrence of roots (**Table 4.4**) and pores (not shown) at the study sites reported here. The fact that differences are apparently less distinct than those reported by Norton et al. (2004) probably results from the necessity to select some paired sites where soil development factors are less than perfectly matched and/or where native plant communities are degraded.

Soils beneath the annual grasses have significantly higher silt and clay contents than the sagebrush sites (**Table 4.5**), perhaps a result of the relatively dense, continuous vegetation cover capturing more wind-blown sediments. Soils of annual grass sites also consistently have higher contents of mineral N, as well as mineral N occurring as NO_3-N. This suggests that the annual grasses create a more mineralizing environment than their sagebrush counterparts, possibly due to relatively high annual inputs of more decomposable litter and roots deposited on or near a somewhat more aerated soil surface. Annual grass sites also have higher concentrations of soil K in near-surface horizons than their sagebrush counterparts, except that surface soils beneath sagebrush canopies have the highest K levels. This is probably due to increased fire frequency in the annual grass-invaded sites, which may lead to accumulation K in ash. High levels of K beneath sagebrush canopies may result from accumulation of

Table 4.1. Average vegetation cover by site and treatment.

		Soil Cover						
Site	**Treatment**	**Bare Soil**	**Plant**	**Native herb.**	**Native shrub**	**Weedy herb.**	**Cheat-grass**	**Medusa-head**
Succor Creek†	Annual Grass	1.5	58					
	Sage interspace	77	34					
	Big sagebrush	15	34					
Lincoln Bench§	Annual Grass	2	0					
	Sage interspace	58	20					
	Big sagebrush	14	20					
Cinder Cone Butte	Annual Grass	17	96	3	0	33	93	0
	Sage interspace	41	34	41	8	0	2	0
	Big sagebrush	2	67	21	0	0	27	0
Canyon Creek	Annual Grass	1	98	0	0	5	1	98
	Sage interspace	76	29	20	0	0	8	1
	Big sagebrush	10	34	28	0	0	5	1
Vernon Hills	Annual Grass	8	63	3	0	5	58	0
	Sage interspace	63	43	34	0	8	0	0
	Big sagebrush	25	63	32	44	5	1	0
Simpson Springs	Annual Grass	12	40	0	0	1	50	0
	Sage interspace	84	18	0	2	18	4	0
	Big sagebrush	5	86	0	86	15	0	0
Izzenhood Ranch	Annual Grass	11	67	68	0	8	63	0
	Sage interspace	27	34	40	1	0	25	0
	Big sagebrush	6	84	20	63	0	34	0
Eden Valley	Annual Grass	13	77	7	0	13	62	0
	Sage interspace	31	0	41	0	7	10	0
	Big sagebrush	0	0	18	76	7	23	0

† Cover-by-species data was not collected for Succor Creek and Lincoln Bench.
§ Vegetation on the Lincoln Bench Annual Grass and Sagebrush sites burned in the summer of 2005 before sampling.

Table 4.2. Average litter composition.

Site	Treatment	Total N		Total C		Lignin		Lignin N		C:N		Lignin N/ Total N	
		——————— % ———————											
	Annual Grass	0.80	a†	25.2	a	47.4	a	0.19		36.0	a	0.226	
All Sites	Sage interspace	0.58	b	22.7	a	52.9	a	0.16		42.7	a	0.308	
	Big sagebrush	0.66	b	16.4	b	64.0	b	0.20		26.0	b	0.307	
	Annual Grass	0.99		34.21	a	31.4	a	0.20	b	39.6	a	0.194	c
Succor Creek	Sage interspace	0.83		22.20	b	53.8	b	0.27	ab	26.5	ab	0.328	b
	Big sagebrush	0.73		12.29	c	67.4	c	0.28	a	16.9	b	0.391	a
	Annual Grass	1.48	a	24.31	a	56.8	b	0.57	a	16.4		0.382	b
Lincoln Bench§	Sage interspace	0.45	b	8.31	b	85.0	a	0.41	ab	18.6		0.918	a
	Big sagebrush	0.43	b	7.66	b	82.9	a	0.24	b	19.0		0.599	ab
	Annual Grass	0.80	a	18.08	ab	62.8		0.17		22.1		0.210	
Cinder Cone Butte	Sage interspace	0.68	a	18.92	a	67.8		0.10		28.0		0.148	
	Big sagebrush	0.46	b	12.05	b	71.7		0.13		26.8		0.296	
	Annual Grass	0.61	a	27.95	a	42.5	b	0.13		47.5	a	0.207	
Canyon Creek	Sage interspace	0.44	b	16.37	b	68.6	a	0.11		36.4	ab	0.260	
	Big sagebrush	0.53	ab	13.82	b	72.6	a	0.13		26.3	b	0.250	
	Annual Grass	0.70		24.82	b	41.9	b	0.16	a	35.6	b	0.224	a
Vernon Hills	Sage interspace	0.73		37.75	a	17.2	c	0.07	b	53.4	a	0.090	b
	Big sagebrush	0.68		13.57	c	58.9	a	0.18	a	20.4	c	0.273	a
	Annual Grass	0.42		21.25		52.0	b	0.07		51.0	a	0.178	
Simpson Springs	Sage interspace	0.52		19.18		64.7	ab	0.07		36.7	b	0.156	
	Big sagebrush	0.50		13.60		74.5	a	0.09		27.2	b	0.180	
	Annual Grass	0.75	ab	32.44		29.0	b	0.08	b	45.0	ab	0.100	b
Izzenhood Ranch	Sage interspace	0.48	b	24.81		46.5	ab	0.11	b	57.0	a	0.254	a
	Big sagebrush	0.86	a	25.2		50.3	a	0.24	a	30.5	b	0.284	a
	Annual Grass	0.61	ab	18.4	b	63.1	a	0.19		30.7	b	0.313	
Eden Valley	Sage interspace	0.51	b	34.3	a	28.4	b	0.13		85.2	a	0.260	
	Big sagebrush	1.07	a	33.2	a	37.4	b	0.28		41.0	ab	0.245	

† Different letters following means within a column denote significant differences at P<0.05.
§ Vegetation on the Lincoln Bench treatments burned in the summer of 2005 before sampling.

Table 4.3. Selected properties of top three horizons.

	Thickness (cm)				**Bulk Density (g cm^{-3})**			
	Sagebrush	Ann Grs.	*% diff.*	t-test P	Sagebrush	Ann Grs.	*% diff.*	t-test P
A horizon	7.13	6.06	*-14.9*	0.08	1.01	1.21	*19.8*	0.18
Subsurface 1	11.63	13.06	*12.4*	0.26	1.11	1.34	*21.5*	0.15
Subsurface 2	15.88	18.38	*15.7*	0.24	1.37	1.43	*4.9*	0.39
	pH				**Gravel %**			
	Sagebrush	Ann Grs.	*% diff.*	t-test P	Sagebrush	Ann grs.	*% diff.*	t-test P
A horizon	7.38	7.36	*-0.3*	0.46	3.63	3.92	*7.8*	0.35
Subsurface 1	7.88	7.52	*-4.5*	0.27	1.89	6.41	*238.2*	0.07
Subsurface 2	8.23	8.21	*-0.3*	0.42	4.39	2.94	*-33.2*	0.29

Table 4.4. Soil morphological properties by horizon in paired soil profiles.†

Hor-izon	Depth	Text. Class	Sand	Silt	Clay	Rock Frags.	Structure			Clay Films			Roots				pH	$CaCO_3$	Bnd
	—cm—		——	%	——		*Grade*	*Size*	*Type*	*Freq*	*Thickness*	*Type*	*V. Fi*	*Fi*	*Med*	*Co*		%	
Succor Creek Sagebrush																			
A	0 - 5	Sl	53	35	12	10	Mod	Fi/med	Pl				Mn	Cm			7.67	1.0	CS
Bt1	5 - 13	Gl	49	35	16	15	Str	Fi/med	Pl				Cm	Cm	Cm		7.92	0.2	AW
Bt2	13 - 23	L	46	32	22	0	Mod	Fi/med	Sbk				Fw	Cm	Cm		7.65	0.2	CW
Bt3	23 - 33	L	47	29	24	0	Mod	Fi/med	Sbk				Cm	Cm	Cm		8.57	3.6	GS
Bk	33 - 45	Sl	62	22	16	4	Mod	Fi/med	Sbk				Fw	Cm	Cm		6.98	18.0	CS
C1	45 - 94	Gsl	70	20	10	24	Ms							Fw				30.2	AS
2CR1	94 - 113	Sl/scl	60	20	20	-	Fissile rock										7.86	15.2	
2CR2	113- 120	Sl	65	33	2	-	Augered										8.54	2.3	
Succor Creek Annual Grass																			
A	0 - 6	Sl	53	37	10	4	Wk	Fi	Pl				Mn				7.32	0.3	S
E	6 - 19	L	47	45	8	3	Mod	Co	Pl				Cm				7.76	0.4	A
Bt1	19 - 23	Cl	34	30	36	11	Str	fine	Pr	Mn	Thk	Pf	Cm				8.04	<0.2	AS
Bt2	23 - 36	Gcl	32	34	34	16	Mod	Co	Pr	Cm	Mod thk	Pf		Cm			8.00	<0.2	GS
Btk	36 - 51	Gcl/c	30	30	40	29	Mod	Fi	Abk	Cm/mn	Thn	Pf		Cm			8.06	1.1	GS
BC	51 - 86	Gc	27	29	44	15	Wk/mod	Fi/med	Sbk	Cm	Thn/mod thk	Pf	VFw				8.35	4.5	GS
C1	86 - 115	Gsil	39	56	5	20	Ms/wk		Pl				VFw				9.06	2.1	AS
CR1	115 - 150	Sl	47	49	4		Ms/wk											1.3	CS
	115 - 130		§			15	Augered										9.13	1.4	
2CR2	130 - 145	Gl/sl	46	47	7	-	Augered										9.09	1.1	
2CR3	145 - 175	C	42	10	48	-	Augered										6.55	1.2	
2CR4	175 - 200	C	42	6	52	-	Augered										7.30	0.8	
Lincoln Bench Sagebrush																			
A	0 - 8	Sil	38	52	10	2	Mod	Fi	Pl				Mn				7.23	0.3	CS
AB	8 - 20	Sil	35	55	10	13	mod/str	Med	Pl				Cm				7.68	0.3	AS
Bt1	20 - 39	Sil	27	51	22	3	Str	Fi/med	Pr				Cm		Cm	Fw	7.65	0.3	CS
BtC	39 - 48	Sil	30	56	14	5	Mod	Fi/med	Sbk				Fw				7.95	<0.2	AS
BC	48 - 74	Sl	55	39	6	5	mod/str	Fi/med	Sbk				VFw		Cm		8.42	1.8	AS
C1k	74 - 86	Sl	66	26	8	0	Ms											26.3	AS
2C2k	86 - 100	Gls	73	25	2	21	Ms										9.25	46.8	
3C3	100 - 150	Sl	63	35	2	1	Augered										7.23	5.3	

Hor-izon	Depth	Text. Class	Sand	Silt	Clay	Rock Frags.	Structure			Clay Films			Roots				pH	$CaCO_3$	Bnd
	cm		*%*				*Grade*	*Size*	*Type*	*Freq*	*Thickness*	*Type*	*V. Fi*	*Fi*	*Med*	*Co*		*%*	
Lincoln Bench Annual Grass																			
A	0 - 5	Gsil	32	59	9	22	Mod	Fi/med	Pl				Mn				8.53	0.3	CS
2BC	5 - 22	Vgsil	34	54	12	60	Str	Fi/med	stratified				Fw				8.55	<0.2	A
3C	20 -					9											8.35	0.4	
4Bt1	22 - 45	Sil	34	55	11	7	mod/str	Med	Sbk	Fw	Thn	Pf	Fw				7.20	0.3	GS
4Bt2	45 - 70	Sil	33	57	10	5	Wk/mod	Med	Pr	Cm	Thn/mod thk	Pf	VFw				7.54	0.3	GS
4Bt3	70 - 95	Gsil	32	62	6	16	Str	Fi/med	Abk	Cm/mn	Thn/mod thk	Pf					7.66	0.4	
4BC	95 - 123	Sil	32	62	6	11	Str	Fi/med	Sbk								7.50	1.6	
4Ck1	123 - 150	Sl	50	44	6	9	Ms/wk	Fi/med	Sbk								8.27	15.1	
4Ck2	160 - 190					7	Augered										8.15	23.0	
Cinder Cone Butte Sagebrush																			
A	0 - 6	Ls	84	11	5	7	Wk	Fi/med	Sbk				Mn	Mn			8.30	<0.2	CW
BC1	6 - 18	Ls	82	13	5	1	Wk	Fi	Sbk				Cm	Cm			8.72	0.3	CS
BC2	18 - 33	Ls	78	15	7	4	Wk	Med	Pr				Fw	Fw			9.75	0.3	GS
BC3	33 - 68	Ls	87	7	6	2	Wk	Med	Pr				Fw	Fw	Fw		10.01	0.3	GS
BC4	68 - 93	S/ls	88	6	6	1	Wk	Med	Sbk				VFw				8.42	<0.2	GS
C	93 - 110	S/ls	88	6	6	1	Ms						Fw		Fw		8.15	0.2	
Cinder Cone Butte Annual Grass																			
A	0 - 6	Sl	54	36	10	0	Wk	Med	Pl				Mn				7.67	0.3	CS
Bt1	6 - 17	L	47	35	18	0	Wk	Med	Pr				Cm		Fw		7.94	<0.2	CS
Bt2	17 - 33	L/Cl	42	31	27	1	Mod	Fi/med	Pr	Mn	Thn/mod thk	Pf	Cm				7.81	<0.2	GS
Bt3	33 - 48	Scl	58	18	24	1	Wk	Med	Pr	Mn	Mod thk	Pf	Cm				8.64	0.4	CS
BtC	48 - 58	Sl	65	16	19	5	Ms						Fw				8.62	0.3	CS
2C	58 - 63	Vgsl	70	20	10	35	Ms										8.95	<0.2	
3C1	100 - 130	Ls	82	16	2	0	Augered										6.80	1.6	
3C2	140 - 150	Ls	81	17	2	0	Augered										3.85	1.6	
3C3	200 - 250	Ls	85	13	2	0	Augered										7.93	2.1	

Horizon	Depth (cm)	Text. Class	Sand (%)	Silt (%)	Clay (%)	Rock Frags. (%)	Structure: *Grade*	Structure: *Size*	Structure: *Type*	Clay Films: *Freq*	Clay Films: *Thickness*	Clay Films: *Type*	Roots: *V. Fi*	Roots: *Fi*	Roots: *Med*	Roots: *Co*	pH	$CaCO_3$ (%)	Bnd
Canyon Creek Sagebrush																			
A	0 - 13	Sil/l	37	50	13	4	Augered										8.19	0.2	
AB	13 - 20	L	35	48	17	4	Augered											<0.2	
Bt1	20 - 30	Cl	33	35	32	0	Augered										6.44	0.3	
Bt2	30 - 38	C	35	15	50	0	Augered										7.91	0.3	
Bt3	38 - 50	Cl/c	27	33	40	0	Augered										7.74	0.3	
Bt4	50 - 60	Cl	32	38	30	0	Augered										8.03	<0.2	
Cqm	60 - 65+						Augered												
Canyon Creek Annual Grass																			
A	0 - 8	L	36	43	21	10	Wk	Med	Pl				Mn				6.84	0.3	CS
Bt1	8 - 26	C	28	30	42	0	Mod	Med	Pr				Cm				7.90	<0.2	GS
Bt2	26 - 50	C	32	22	46	3	Str	Med	Pr				Fw				8.24	<0.2	CS
Bt3	50 - 61	C	31	20	49	2	Mod	Fi	Abk				VFw				8.82	0.8	CW
Cqm	61 - 63					1	Ms										9.14	1.9	CW
	63 - 70					3	?										9.24	1.0	
	63 - 70					10											8.57	33.0	
Vernon Hills Sagebrush																			
A	0 - 8	L	45	40	15	0	Wk	Med	Pl					Mn	Mn		8.07	17.5	CW
Bt1	8 - 30	L	34	46	20	0	Wk/mod	Fi	Pr				Fw	Mn	Mn		8.63	20.1	CW
Bt2	30 - 65	L	34	42	24	1	Wk	Fi/med	Pr	Cm	Thn	Pf		Mn	Fw		8.86	20.5	CS
Bt3	65 - 90	Sl/scl	57	23	20	1	Wk	Fi	Sbk				Mn		Mn		8.78	16.6	CS
BC	90 - 110	L/scl	51	28	21	12	Ms						Fw				8.72	14.0	
C	150 - 160	L	41	43	16	0	Augered										8.86	11.4	
Vernon Hills Annual Grass																			
A	0 - 6	L	39	47	14	0	Mod	Fi/med	Pl				Mn				8.46	10.5	C
AB	6 - 18	L	41	43	16	0	Mod	Fi	Pl				Cm				8.97	12.4	G
Bk1	18 - 40	L	43	39	18	0	Mod	Fi/med	Sbk				Cm				9.45	18.7	G
Bk2	40 - 65	L	48	38	14	1	Mod	Fi/med	Sbk				Fw				9.16	18.7	G
2BC	65 - 88	Gl	42	46	12	30	Wk	Med	Pr				Cm				8.83	15.9	G
3C1	88 - 100	L	44	41	15	0	Ms	?					Fw				6.58	15.1	
4C2	140 - 150	Sil	28	51	21	0	Augered										7.42	8.3	

Hor-izon	Depth	Text. Class	Sand	Silt	Clay	Rock Frags.	Structure			Clay Films			Roots				pH	$CaCO_3$	Bnd
	cm		%				*Grade*	*Size*	*Type*	*Freq*	*Thickness*	*Type*	*V. Fi*	*Fi*	*Med*	*Co*		%	
Simpson Springs Sagebrush																			
A	0 - 8	Sl	66	25	9	3	Wk	Med	Pl					Mn			8.13	8.8	CS
Bk1	8 - 20	Sl	62	28	10	10							Cm	Cm			8.09	8.7	CS
2Bk2	20 - 35	CobSl	69	20	11	40	Mod	Fi/med	Sbk				Cm	Cm	Fw		7.58	10.8	G
3Bk3	35 - 67	Sl	69	21	10	6	Mod	Fi/med	Sbk				Cm		Cm		7.79	11.8	G
4BC	67 - 90	CobSl	70	20	10	20	Wk	Fi	Sbk				Mn				8.06	11.8	G
5C1	90 - 100	Sl	78	12	10	3	Ms						Cm	Cm			8.77	10.5	
5C2	160 - 170	Ls	82	11	7	5	Augered										9.21	8.3	
Simpson Springs Annual Grass																			
A	0 - 8	L	39	47	14	9	Wk/mod	Fi	Pl				Mn				6.54	12.9	CW
Btk1	8 - 22	L	39	42	19	7	mod/str	Med	Pl				Cm				7.54	17.5	GS
Btk2	22 - 50	L	40	39	21	2	Mod	Med	Sbk				Fw				7.75	14.0	GS
Btk3	50 - 60	Scl	54	25	21	5	Mos	Fi/med	Sbk	Cm	Mod thk	Pf	Cm				6.15	11.3	CS
2BC	60 - 78	VcobLs	84	7	9	90	Wk		Sbk				Fw				8.65	9.1	AI
2C1	78 - 95	VcobLs	86	7	7	95	Sg							Fw			9.15	5.5	CI
3C2	95 - 115	S	95	2	3	2	Sg										8.26	0.7	
3C3	140 - 145	Ls	79	13	8	2	Augered										8.13	8.3	
3C4	145 - 155					6	Augered										8.26	4.4	
Izzenhood Ranch Sagebrush																			
A	0 - 7	Gl	48	44	8	32	Wk	Fi/med	Pl				Mn	Mn			10.34	<0.2	CW
2AB	7 - 18	L	50	40	10	8	Mod	Fi/med	Pl				Cm	Cm	Cm		10.06	<0.2	GS
3Bw1	18 - 29	Vgsl	64	28	8	61	Mod	Fi/med	Sbk				Cm	Cm	Mn		10.24	0.2	CS
4Bw2	29 - 42	Sl	75	19	6	13	mod/str	Fi/med	Sbk				Fw	Fw	Fw		8.53	<0.2	CS
4BC	42 - 50	Ls	84	11	5	4	Wk/mod	Fi/med	Sbk					Cm	Cm		8.63	<0.2	CW
4Ckm1	50 - 70	Sl	79	11	10	11	Cemented	Fi/med	Sbk					Cm	Cm		9.00	8.2	CW
4Ckm2	70 - 84	Sl	73	10	17	6	Cemented	Fi/med	Sbk					Cm	Cm		9.11	2.0	CW
4Ckm3	84 - 100	Ls	81	9	10	10	Cemented	Fi	Sbk					Cm			9.26	10.3	
4Ckm4	120 - 125	Ls	86	10	4	7	Augered										9.36	0.5	

Hor-izon	Depth	Text. Class	Sand	Silt	Clay	Rock Frags.	Structure			Clay Films			Roots				pH	$CaCO_3$	Bnd
	——cm——		———	——%——	———		*Grade*	*Size*	*Type*	*Freq*	*Thickness*	*Type*	*V. Fi*	*Fi*	*Med*	*Co*		*%*	
Izzenhood Ranch Annual Grass																			
A	0 - 6	Sl	60	35	5	11	Mod	Med	Pl					Mn			9.46	<0.2	CW
2AB	6 - 21	Gsl	62	32	6	22	Mod	Fi	Sbk				Cm		Cm	Cm	8.47	<0.2	CS
3Bw1	21 - 37	Sl	70	22	8	12	Wk	Med/co	Sbk						Cm		8.14	<0.2	CS
3Bw2	37 - 43	Sl	76	17	7	12	mod/str	Fi/med	Sbk	Cm	Thn	Pf	Fw		Cm		9.20	0.2	CI
3BC	43 - 59	Ls	79	13	8	4	Wk/mod	Fi/med	Sbk	Cm	Thn	Pf		Cm	Cm		9.22	<0.2	CS
3Cm1	59 - 87	Ls	79	14	7	4	Ms										9.44	<0.2	
3Cm2	87 - 105	Ls	81	9	10	7	Ms										9.93	0.7	
4Ckm1	130 - 140	Gsl	62	20	18	17	Augered										10.16	8.1	
4Ckm2	150 - 160	Vgsl	81	10	9	37	Augered										10.34	5.3	
Eden Valley Sagebrush																			
A	0 - 5	L	46	46	8	1	Mod	Fi/med	Sbk				Mn				8.90	<0.2	CW
AB	5 - 12	L	42	48	10	1	Mod	Fi/med	Pl				Cm	Cm			8.53	<0.2	CS
Bt1	12 - 23	Sil/l	40	50	10	0	Str	Fi/med	Sbk	Cm	Thn	Pf	Cm		Cm	Cm	8.75	0.3	CS
Bt2	23 - 33	Sil	37	51	12	1	Str	Fi/med	Sbk	Mn	Thn/mod thk	Pf		Cm	Cm		9.20	0.3	CS
2Bk1	33 - 48	L	51	41	8	3	Str	Fi	Abk	Cm	Thn/mod thk	Pf		Cm	Cm		8.41	5.2	CS
2Bk2	48 - 58	L/sl	50	43	7	0	Str	Fi/med	Abk	Cm	Thn	Pf		Cm	Cm		8.71	3.7	CW
2Ckm	58 - 67	Sl	61	31	8	0											8.61	1.3	
Eden Valley Annual Grass																			
A	0 - 4	L	47	41	12	5	Mod	Fi/med	Sbk				Mn				10.01	<0.2	CS
AB	4 - 13	L	45	42	13	5	Str	Fi/med	Pl				Cm				8.38	<0.2	CS
Btk1	13 - 22	L	45	41	14	5	Mod	Med	Pr/pl				Cm				8.71	<0.2	CS
Btk2	22 - 34	L	46	40	14	5	Mod	Med	Sbk				Cm				8.95	0.2	CS
Btk3	34 - 53	L	47	38	15	5	Mod	Fi/med	Sbk				Cm				9.21	3.9	CW
2Ckm1	53 - 84					20	Cemented										9.86		
3Ckm2	84 - 100	Sl/ls	79	12	9	1	Sg										10.10	36.3	

† Abbreviations: A, abrupt; Abk angular, blocky; C, clear; C, clay; Cl, clay loam; Cm, common; Co, coarse; Fi, fine; Fw, few; G, gradual; Gcl, gravelly clay loam; Gl, gravelly loam; Gls, gravelly loamy sand; Gsil, gravelly silt loam; Gsl, gravelly sandy loam; L, loam; Ls, loamy sand; Med, medium; Mn, many; Mod, moderate; Ms, massive; Pf, ped faces; Pl, platy; Pr, prismatic; Sg, single grain; Sl, sandy loam; S, smooth; Sbk, subangular blocky; Scl, sandy clay loam; Sicl, silty clay loam; Sil, silt loam; Sl, sandy loam; Str, strong; Thk, thick; Thn, thin; Vgl, very gravelly loam; Vgls, very gravelly loamy sand; Vgsil, very gravelly silt loam; W, wavy; Wk, weak.

§ Missing values denote insufficient or missing samples.

litter that is incorporated into A horizons. Site by site comparisons (**Tables 4.6 and 4.7**) generally confirm the overall averages reported in **Table 4.5** but also show that there is considerable variability in these paired site comparisons. **Table 4.6** shows a rise in mineral N levels with depth at several of the sites in both annual grass and sagebrush soils, suggesting movement below the root zone possibly with preferential flow.

Soils of the restoration study sites all lie on what appear to be either active or relict alluvial surfaces, some with an eolian component. Most sites lie on deep alluvium with strata of fine sands and gravelly or cobbly loams (**Table 4.4**). Strong soil development in the form of distinct argillic horizons are superimposed on the alluvial strata. The Succor Creek site has what appears to be a paralithic horizon of decomposed biotite-rich bedrock at 115 cm. All the sites except the Canyon Creek site have accumulations of $CaCO_3$ within about 40 cm of the surface, with strongly indurated calcic horizons at about 50 cm at the Izzenhood Ranch and Eden Valley sites. The Canyon Creek site has a duripan (silicon accumulation) beginning just below 50 cm below the surface, but no free $CaCO_3$. Surface soil textures are loams and sandy loams except for the Lincoln Bench site, which is silt loam probably of eolian origin. The Canyon Creek site has the heaviest subsoils with clay textures below a loam surface horizon.

Soil organic matter constituents are relatively constant among the eight restoration study sites, with lowest levels of organic C and N in surface soils occurring at the Izzenhood Ranch site and the highest at the Succor Creek and Lincoln Bench sites (**Table 4.7**).

Table 4.5. Anova results for selected soil properties for five-rep samples.

Depth	**Sand**			**Silt**			**Clay**			**pH**			**C:N**		
cm	%														
	AG	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**
0-10	46	52	53	41 a	37 ab	37 b	13 a	10 b	10 b	7.6	7.8	7.8	14.5	15.9	14.6
10-20	44	51	50	38	35	36	18 a	14 b	14 b	8.3	8.3	8.2	13.5	14.4	15.5

Depth	**C**			**N**			**Mineral N as NO_3-N**			**NO_3-N**			**NH_4-N**		
	%									*mg kg^{-1}*					
	AG	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**
0-10	1.218	1.096	1.089	0.087	0.072	0.080	49.4 a	36.7 b	33.2 b	4.00 a	1.43 b	1.97 b	2.50	3.57	4.82
10-20	0.704	0.713	0.812	0.053	0.052	0.052	49.1 a	36.8 b	31.5 b	1.74 a	0.91 b	1.09 b	1.38	1.66	2.05

Depth	**30d PMN**			**Total P**			**Available P**			**K**		
	mg kg^{-1}			%			*mg kg^{-1}*					
	AG	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**
0-10	11.80	10.52	13.21	0.063	0.059	0.061	18.9 ab	15.3 b	21.2 a	698 a	527 b	726 a
10-20	5.33	6.04	6.10	0.051	0.047	0.049	10.2	8.2	10.2	722 a	525 b	581 b

Depth	**Fe**			**Mn**		
	mg kg^{-1}					
	AG	**SI**	**BS**	**AG**	**SI**	**BS**
0-10	12.09	9.85	9.59	17.56	14.06	14.40
10-20	5.59	5.51	5.13	8.68	8.59	10.10

† AG, annual grass; SI, sagebrush interspace; BS, big sagebrush.

1. § Different letters following means within a row denote significant differences at the $P<0.05$ level.

Table 4.6. Moisture, bulk density, and nutrients by horizon in paired soil profiles.

Horizon depth	Moisture	BD	C	N	C:N	P	Avail P	K	NH4-N	NO3-N	Nmin as NO3	30d PMN	Fe	Mn
cm	*%*	*g cm^{-3}*	——*%*——			——*mg kg^{-1}*——					*%*	——*mg kg^{-1}*——		
Succor Creek Sagebrush														
0 - 5	7		1.580	0.103	15.3	0.106	28.5	871	1.23	39.58	96.98	40.82	12.69	20.20
5 - 13	11	1.51	0.669	0.058	11.5	0.094	13.5	721	0.44	7.14	94.24	7.58	4.72	7.76
13 - 23	20	1.34	0.598	0.050	12.0	0.038	4.0	254	0.21	5.79	96.51	6.00	3.92	4.22
23 - 33	25	1.46	1.090	0.060	18.2	0.080	8.0	175	2.93	4.67	61.49	7.60	1.80	1.82
33 - 45		1.39	0.746	0.094	7.9	0.100	12.8	136	3.85	1.62	29.60	5.47	1.20	1.78
45 - 94	13	1.07	0.918	0.099	9.3	0.076	2.3	116	1.91	2.67	58.25	4.58	0.66	0.98
94 - 113	32		0.212	0.034	6.2	0.050	37.6	134	1.29	0.99	43.42	2.28	0.96	0.60
113 - 200			0.234	0.017	13.8	0.008	3.4	45	0.79	0.65	45.05	1.43	2.59	0.64
Succor Creek Annual Grass														
0 - 6	5	1.50	1.580	0.109	14.5	0.075	39.2	1004	5.82	13.83	50.09	27.61	17.04	53.00
6 - 19	8	1.58	0.472	0.043	11.0	0.046	13.5	875	2.50	9.63	79.36	12.13	4.45	12.88
19 - 23	40	1.81				0.010	13.3	561	0.74	4.19	84.95	4.93	13.39	1.37
23 - 36	35	1.85	0.448	0.032	14.0	0.019	34.8	301	2.36	0.15	5.89	2.51	41.65	0.92
36 - 51	53-84	1.62	0.244	0.032	7.6	0.043	10.8	288	9.39	1.87	16.62	11.27	2.74	2.74
51 - 86	74	1.69	0.232	0.044	5.3	0.050	6.9	283	3.16	1.92	37.74	5.08	1.23	0.34
86 - 115	53	1.56	0.276	0.039	7.1	0.016	6.0	221	1.40	2.28	61.97	3.68	1.32	0.20
115 - 150	64		0.161	0.047	3.4	0.016	3.7	257	4.85	2.53	34.31	7.38	2.90	0.36
115 - 130		1.50	0.149	0.032	4.7	0.018	5.2	204	3.94	3.62	47.87	7.56	4.00	0.31
130 - 145			0.179	0.044	4.1	0.015	1.8	225	3.16	2.88	47.69	6.03	1.47	0.12
145 - 175		1.66	0.161	0.041	3.9	0.023	<1.0	234	2.71	3.08	53.25	5.79	3.26	0.12
175 - 200		1.68				0.018	<1.0	247	2.83	2.47	46.62	5.29	3.59	0.24
Lincoln Bench Sagebrush														
0 - 8	6	1.23	1.070	0.090	11.9	0.054	63.8	1026	244.99	1.94	0.79	246.93	35.70	98.91
8 - 20	6	1.35	0.493	0.042	11.7	0.040	18.5	823	21.67	7.11	24.70	28.78	10.50	19.33
20 - 39	29	1.68	0.351	0.044	8.0	0.027	1.4	546	1.96	3.14	61.49	5.10	3.45	8.73
39 - 48		1.67	0.314	0.035	9.0	0.035	1.8	527	1.79	0.64	26.17	2.43	2.21	2.15
48 - 74		1.57	0.317	0.023	13.8	0.025	<1.0	559	1.11	0.29	20.72	1.40	0.88	0.72
74 - 86		1.23	0.749	0.080	9.4	0.023	1.4	461	0.36	0.57	61.49	0.93	1.06	1.11
86 - 100		1.62	1.740	0.127	13.7	0.038	2.2	303	2.20	0.63	22.32	2.83	0.60	0.84
100 - 150			0.224	0.031	7.2	0.034	2.2	560	0.49	0.18	27.18	0.67	0.56	0.64

Horizon depth *cm*			Mois-ture *%*	BD *g cm⁻³*	C *%*	N *%*	C:N	P *mg kg⁻¹*	Avail P *mg kg⁻¹*	K *mg kg⁻¹*	NH4-N *mg kg⁻¹*	NO3-N *mg kg⁻¹*	Nmin as NO3 *%*	30d PMN *mg kg⁻¹*	Fe *mg kg⁻¹*	Mn *mg kg⁻¹*
Lincoln Bench Annual Grass																
0	-	5	4	1.16	2.590	0.214	12.1	0.053	37.5	712	1.08	59.43	98.22	60.51	30.51	42.88
5	-	22		1.32	0.363	0.036	10.1	0.031	5.5	534	0.58	3.02	83.94	3.60	7.63	8.56
20	-			1.40	0.405	0.036	11.3	0.030	3.9	625	0.94	3.80	80.14	4.74	9.15	11.13
22	-	45	16	1.43	0.294	0.037	7.9	0.032	3.0	592	0.55	3.30	85.81	3.84	5.19	10.14
45	-	70	14	1.55	0.309	0.037	8.4	0.037	2.2	761	4.99	12.11	70.80	17.10	2.86	4.86
70	-	95		1.63	0.259	0.028	9.3	0.046	4.0	930	0.53	0.46	46.93	0.99	2.36	1.75
95	-	123	17	1.51	0.506	0.031	16.3	0.077	7.4	872	1.84	1.21	39.64	3.05	1.79	1.23
123	-	150	13	1.43	0.275	0.041	6.7	0.053	10.5	839	1.56	1.70	52.17	3.26	0.50	0.63
160	-	190						0.067	25.4	777						
Cinder Cone Butte Sagebrush																
0	-	6	4		1.600	0.099	16.2	0.021	16.9	183	3.91	49.12	92.63	53.03	25.46	20.66
6	-	18	4		0.248	0.019	13.1	0.018	9.7	164	0.83	2.61	75.73	3.44	6.31	4.30
18	-	33	5	2.04	0.204	0.018	11.3	0.018	6.5	233	0.70	1.36	66.16	2.06	3.90	6.09
33	-	68	3	1.75	0.170	0.017	10.0	0.011	2.6	155	0.56	0.87	61.13	1.43	2.43	4.94
68	-	93		1.93	0.124	0.016	7.8	0.010	4.1	135	0.75	0.46	38.15	1.20	3.41	4.33
93	-	110	4	1.90	0.124	0.013	9.5	0.011	2.5	173	0.68	0.20	22.50	0.87	1.72	2.34
Cinder Cone Butte Annual Grass																
0	-	6	4	1.54	0.908	0.075	12.1	0.042	31.0	483	0.16	13.42	98.85	13.57	10.94	14.20
6	-	17	7	1.50	0.712	0.057	12.5	0.036	27.0	629	0.40	8.26	95.42	8.65	6.41	8.63
17	-	33		1.60	0.488	0.051	9.6	0.028	11.2	482	1.15	4.28	78.80	5.43	7.52	10.08
33	-	48		1.87	0.273	0.032	8.5	0.014	1.6	270	0.51	3.12	86.06	3.63	6.30	5.25
48	-	58		1.83				0.015	2.2	215						
58	-	63		1.83				0.015	<1.0	164	1.01	1.22	54.83	2.23	2.56	3.36
100	-	130		1.50	0.217	0.025	8.7	0.019	<1.0	177	0.86	0.18	16.94	1.04	1.04	0.98
140	-	150		1.51	0.120	0.016	7.5	0.033	<1.0	102	0.20	1.34	86.92	1.54	1.12	0.74
200	-				0.297	0.012	24.8	0.036	2.3	88	0.28	1.07	79.47	1.34	1.02	1.40

Horizon depth	Mois-ture	BD	C	N	C:N	P	Avail P	K	NH4-N	NO3-N	Nmin as NO3	30d PMN	Fe	Mn
cm	*%*	*g cm^{-3}*	*——%——*			*——mg kg^{-1}——*					*%*	*——mg kg^{-1}——*		
Canyon Creek Sagebrush														
0 - 13			0.879	0.062	14.2	0.033	19.2	294	1.34	12.42	90.29	13.75	14.42	27.82
13 - 20			0.400	0.036	11.1	0.028	8.1	192	1.79	5.69	76.04	7.48	7.78	23.53
20 - 30			0.426	0.044	9.7	0.024	4.1	302	4.42	1.14	20.51	5.56	6.40	11.69
30 - 38			0.358	0.036	9.9	0.022	1.3	389	4.04	2.62	39.31	6.66	3.10	4.21
38 - 50			0.339	0.036	9.4	0.026	1.4	322	4.12	0.79	16.14	4.92	2.39	2.87
50 - 60			0.506	0.038	13.3	0.031	5.3	296	0.82	11.09	93.09	11.92	4.90	10.30
Canyon Creek Annual Grass														
0 - 8	8	1.34	1.480	0.112	13.2	0.048	28.4	314	9.32	10.13	52.08	19.46	25.69	35.61
8 - 26	12	1.69	0.472	0.045	10.5	0.025	8.2	400	3.49	0.67	16.08	4.15	6.81	6.53
26 - 50	38	1.94	0.330	0.032	10.3	0.017	<1.0	324	4.15	0.46	10.03	4.61	2.96	4.23
50 - 61	40	1.86	0.411	0.041	10.0	0.016	<1.0	315	2.53	1.02	28.68	3.54	2.20	1.58
61 - 63		1.61				0.020	2.7	353						
63 - 70		1.28				0.010	1.7	285						
63 - 70		1.83	0.176	0.040	4.4	0.044	12.4	293	2.34	1.77	43.05	4.12	2.02	1.82
Vernon Hills Sagebrush														
0 - 8	6	1.32	1.220	0.115	10.6	0.061	21.8	827	0.96	44.03	97.87	44.98	3.58	10.42
8 - 30	9	1.34	0.318	0.038	8.4	0.036	<1.0	541	0.28	1.57	84.77	1.86	2.94	4.23
30 - 65	6	1.35	0.441	0.055	8.0	0.045	<1.0	215	0.47	0.46	49.68	0.94	2.01	3.00
65 - 90	6	1.39	0.218	0.039	5.6	0.053	5.2	141	1.22	0.17	12.04	1.39	2.64	4.44
90 - 110	20	1.45	0.211	0.040	5.3	0.057	4.7	165	3.02	0.66	17.92	3.68	2.28	3.09
150 - 160			0.153	0.034	4.5	0.044	5.5	174	0.86	1.93	69.17	2.79	1.68	1.40
Vernon Hills Annual Grass														
0 - 6	6	1.26	1.460	0.164	8.9	0.076	22.2	955	1.91	39.53	95.38	41.44	3.31	9.53
6 - 18	8	1.34	1.040	0.106	9.8	0.067	8.7	754	0.37	6.65	94.69	7.03	1.84	4.96
18 - 40	11	1.40	0.559	0.062	9.0	0.052	4.0	804	0.21	3.94	95.01	4.15	1.59	2.74
40 - 65	11	1.30	0.975	0.057	17.1	0.035	1.7	741	3.18	4.48	58.49	7.65	1.07	2.43
65 - 88	16	1.48	0.437	0.055	7.9	0.038	1.5	128	2.26	0.90	28.42	3.15	1.09	1.90
88 - 100	14	1.35	0.246	0.035	7.0	0.040	1.6	135	3.63	1.02	21.94	4.66	2.29	2.91
140 - 150			0.192	0.029	6.6	0.050	3.5	189	2.26	0.35	13.57	2.61	5.86	7.23

Horizon depth	Mois-ture	BD	C	N	C:N	P	Avail P	K	NH4-N	NO3-N	Nmin as NO3	30d PMN	Fe	Mn
cm	*%*	*g cm^{-3}*	*——%——*			*——mg kg^{-1}——*					*%*	*——mg kg^{-1}——*		
Simpson Springs Sagebrush														
0 - 8		1.39	0.828	0.075	11.0	0.083	13.2	377	0.88	22.68	96.24	23.56	4.27	7.51
8 - 20		1.50	0.478	0.045	10.6	0.076	4.9	482	0.09	9.93	99.07	10.02	1.89	3.76
20 - 35		1.59	0.209	0.033	6.3	0.058	1.2	553	0.19	4.28	95.77	4.47	1.49	3.22
35 - 67		1.66	0.300	0.031	9.7	0.055	1.0	591	0.12	2.13	94.85	2.25	1.39	2.50
67 - 90		1.86				0.051	<1.0	532	1.07	2.11	66.32	3.18	1.52	2.80
90 - 100		1.86	0.875	0.016	54.7	0.055	1.7	402	0.14	1.48	91.45	1.62	1.24	1.58
160 - 170			0.154	0.028	5.5	0.068	2.5	304	2.91	12.55	81.19	15.46	1.19	3.21
Simpson Springs Annual Grass														
0 - 8	7	1.51	1.410	0.167	8.4	0.114	17.6	888	0.95	36.88	97.49	37.83	3.70	8.30
8 - 22	15	1.69	0.359	0.043	8.3	0.081	1.8	1029	0.05	1.64	97.25	1.69	1.59	2.54
22 - 50	14	1.54	0.280	0.037	7.6	0.057	<1.0	946	0.05	3.55	98.70	3.60	1.79	1.87
50 - 60	9	1.80	0.222	0.027	8.2	0.048	<1.0	581	1.11	2.44	68.65	3.55	2.35	2.91
60 - 78			0.128	0.019	6.7	0.049	2.6	426	1.13	1.07	48.55	2.20	2.97	4.24
78 - 95			0.168	0.025	6.7	0.072	2.3	236	1.36	0.82	37.70	2.19	2.33	2.31
95 - 115	6		0.112	0.018	6.2	0.072	<1.0	220	0.44	0.36	45.21	0.80	1.36	1.98
140 -			0.191	0.023	8.3	0.065	2.2	348	1.33	0.50	27.37	1.83	1.86	3.66
145 - 155			0.163	0.024	6.8	0.086	2.1	251	0.92	9.54	91.20	10.46	0.92	2.05
Izzenhood Ranch Sagebrush														
0 - 7	4	1.24	1.400	0.095	14.7	0.043	20.6	609	0.95	39.41	97.65	40.36	19.30	23.51
7 - 18	5	1.42	0.507	0.043	11.8	0.028	7.4	709	0.16	2.22	93.15	2.38	2.55	2.87
18 - 29	6	1.70	0.162	0.023	7.0	0.019	1.9	503	0.23	1.07	82.10	1.30	1.48	2.32
29 - 42	6	1.71	0.134	0.018	7.4	0.019	<1.0	398	0.49	1.14	69.90	1.63	1.28	1.04
42 - 50	9	1.79	0.138	0.016	8.6	0.013	<1.0	367	1.12	0.41	26.63	1.52	1.32	1.24
50 - 70		1.75	0.193	0.030	6.4	0.045	11.8	326	4.10	11.32	73.40	15.42	1.08	0.66
70 - 84		1.89	0.257	0.024	10.7	0.027	13.0	346	2.20	35.36	94.15	37.55	1.94	1.44
84 - 100		1.79	0.162	0.031	5.2	0.033	17.7	348	0.28	74.49	99.63	74.77	1.24	1.34
120 - 125			0.140	0.021	6.7	0.022	1.6	304	0.73	52.04	98.61	52.77	1.15	1.21

Horizon depth	Mois-ture	BD	C	N	C:N	P	Avail P	K	NH4-N	NO3-N	Nmin as NO3	30d PMN	Fe	Mn
cm	*%*	*g cm^{-3}*	*——%——*			*mg kg^{-1}*					*%*	*mg kg^{-1}*		
Izzenhood Ranch Annual Grass														
0 - 6	5	1.28	2.290	0.166	13.8	0.055	28.8	535	4.41	53.52	92.39	57.93	26.43	39.21
6 - 21	7	1.46	0.175	0.027	6.5	0.039	2.6	572	0.47	1.47	75.82	1.93	1.58	2.02
21 - 37	8	1.53	0.160	0.017	9.4	0.020	<1.0	347	0.77	1.23	61.56	2.00	1.32	1.90
37 - 43	9	1.79	0.124	0.022	5.6	0.017	<1.0	275	2.52	0.70	21.85	3.23	1.65	3.65
43 - 59	11	1.74	0.138	0.016	8.6	0.017	<1.0	259	3.58	0.54	13.04	4.11	1.70	2.06
59 - 87	12	1.77	0.518	0.044	11.8	0.023	<1.0	267	2.51	2.26	47.31	4.77	1.58	1.60
87 - 105		1.80	0.118	0.014	8.4	0.029	6.4	329	0.41	4.02	90.83	4.43	1.30	0.64
130 - 140						0.033	22.2	596	0.84	146.00	99.43	146.84	1.69	1.23
150 - 160			0.124	0.030	4.1	0.030	17.5	524	0.12	143.25	99.92	143.36	1.53	0.94
Eden Valley Sagebrush														
0 - 5	5	1.31	1.260	0.125	10.1	0.055	31.5	939	0.84	21.37	96.22	22.21	20.28	17.05
5 - 12	5	1.27	0.637	0.060	10.6	0.037	7.9	945	0.09	4.47	97.96	4.57	4.81	5.06
12 - 23	9	1.29	0.435	0.047	9.3	0.034	8.0	739	0.33	3.56	91.57	3.89	2.91	4.37
23 - 33	13	1.38	0.376	0.048	7.8	0.033	2.4	697	0.61	5.66	90.30	6.27	3.47	3.45
33 - 48	10	1.24	0.636	0.086	7.4	0.051	9.1	568	1.81	0.77	29.79	2.58	1.38	1.90
48 - 58		1.49	0.421	0.059	7.1	0.047	8.5	542	3.25	0.66	16.83	3.91	2.19	2.85
58 - 67		1.28	0.569	0.089	6.4	0.029	1.6	455	2.45	1.69	40.74	4.14	1.52	2.99
Eden Valley Annual Grass														
0 - 4	6	1.20				0.050	22.9	754	0.68	24.57	97.31	25.25	13.70	21.67
4 - 13	8	1.44	0.916	0.073	12.5	0.046	11.4	698	0.19	6.87	97.36	7.06	6.34	6.30
13 - 22	10	1.50	0.677	0.054	12.5	0.040	7.5	731	1.49	3.60	70.78	5.09	3.16	2.55
22 - 34	17	1.34	0.684	0.069	9.9	0.039	2.9	675	0.24	4.35	94.70	4.59	2.37	2.29
34 - 53		1.55	0.727	0.093	7.8	0.041	1.0	322	2.78	3.71	57.16	6.49	1.77	1.77
53 - 84														
84 - 100		1.95				0.035	2.4	134	0.00	0.00		0.00		

Table 4.7. Means by site for selected soil physical and chemical properties.

	Depth	Sand %			Silt %			Clay %			pH			X-K ppm		
	cm	AG†	SI	BS	AG	SI	BS	AG	SI	BS	AG	SI	BS	AG	SI	BS
Succor	0-10	46 b§	53 a	49 ab	42 a	34 b	36 b	12 b	13 b	15 a	6.5 b	7.4 a	7.5 a	981 b	938 b	1425 a
Creek	10-20	43	49	48	36	34	34	22	16	18	7.4	7.7	7.9	1051 a	695 b	740 ab
Lincoln	0-10	33 b	35 ab	35 a	56	55	57	11 a	9 ab	8 b	6.5	6.6	6.8	740	732	793
Bench	10-20	33	32	33	54	52	53	13	16	14	7.2 b	7.9 a	7.9 a	726	747	667
Cinder Cone	0-10	58 b	82 a	83 a	32 a	13 b	12 b	10 a	5 b	4 b	6.7	6.7	6.5	279 a	187 ab	250 b
Butte	10-20	51 b	81 a	81 a	33 a	14 b	14 b	16 a	5 b	5 b	7.3	7.3	7.0	281	234	281
Canyon	0-10	36	38	38	45 b	52 a	52 a	18 a	10 b	10 b	7.2	7.4	7.5	298 ab	193 b	341 a
Creek	10-20	35	37	35	39 b	45 a	49 a	26 a	18 ab	16 b	8.0	7.9	7.7	420 ab	207 b	246 b
Vernon	0-10	43	45	44	42	39	39	15	17	17	9.1 b	9.2 ab	9.3 a	1139 a	546 b	901 a
Hills	10-20	41	38	40	40 a	39 a	36 b	19 b	23 a	25 a	9.5	9.3	9.3	1191	696	904
Simpson	0-10	46	67	68	38	20	19	16	12	13	9.3 b	9.4 ab	9.3 a	693 a	416 b	489 b
Springs	10-20	42 b	67 a	64 a	35 a	19 b	21 b	23 a	14 b	15 b	9.5 a	9.4 ab	9.3 b	765 a	507 b	508 b
Izzenhood	0-10	59 a	52 b	53 ab	33 b	40 a	41 a	8 a	9 a	6 b	7.7	7.9	7.9	744	599	709
Ranch	10-20	62	57	55	29 b	33 ab	38 a	9 a	10 a	7 b	8.4	8.6	8.1	661	522	584
Eden	0-10	47	47	49	41	44	42	11 a	9 b	9 b	8.0	7.5	7.8	711	609	902
Valley	10-20	47 a	44 b	44 ab	39 b	44 a	45 a	14	12	11	8.7	8.5	8.6	680	596	720

	Depth	% C			% N			C/N			NO3-N mgkg			NH4-N mgkg		
	cm	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**
Succor	0-10	1.61	1.70	1.93	0.110	0.111	0.132	14.7	15.2	14.5	9.89	3.03	7.00	4.88	3.67	4.73
Creek	10-20	0.85 b	0.99 b	1.24 a	0.060 b	0.072 ab	0.081 a	13.9 b	13.8 b	15.4 a	4.43	1.53	2.84	2.13	1.75	2.72
Lincoln	0-10	1.61 a	1.11 ab	0.77 a	0.116 a	0.079 ab	0.059 b	13.9	14.0	13.3	3.00 a	0.46 b	0.86 b	2.89	14.85	22.21
Bench	10-20	0.68	0.65	0.50	0.053	0.048	0.041	12.6 ab	13.4 a	12.3 b	1.41	0.50	0.53	1.79	4.97	5.24
Cinder Cone	0-10	1.03 a	0.61 ab	0.50 b	0.061 a	0.037 ab	0.030 b	16.7	16.0	16.4	2.46 a	0.61 b	0.91 b	3.15 a	1.18 b	1.41 b
Butte	10-20	0.76 a	0.39 b	0.37 b	0.048 a	0.025 b	0.024 b	15.4	15.6	15.2	1.41 a	0.36 b	0.80 b	1.97 a	0.97 ab	1.28 b
Canyon	0-10	0.97 a	0.57 b	0.66 ab	0.065 a	0.037 b	0.043 ab	15.2	15.0	15.2	0.32	0.34	0.38	1.92	2.04	2.00
Creek	10-20	0.75 a	0.44 b	0.50 b	0.047 a	0.030 b	0.033 b	15.9	14.5	14.9	0.50 a	0.33 ab	0.21 b	1.58	1.30	1.32
Vernon	0-10	1.32 ab	1.01 b	1.44 a	0.107	0.100	0.149	12.4	10.3	10.2	10.51 a	2.96 b	2.90 b	1.52 ab	0.96 b	2.02 a
Hills	10-20	0.82	1.09	1.67	0.066	0.111	0.089	12.5	10.1	21.9	3.28	1.40	2.10	0.93 b	1.23 b	1.96 a
Simpson	0-10	1.27	0.98	1.09	0.093	0.093	0.099	14.3	11.9	12.3	2.83	2.20	2.38	1.34	1.02	2.56
Springs	10-20	0.61	0.72	1.04	0.059	0.057	0.072	11.3	12.8	15.6	1.29	1.46	1.51	0.50	1.35	1.89
Izzenhood	0-10	0.72	0.65	0.68	0.047	0.042	0.044	15.4	15.4	15.4	1.40	0.49	0.44	2.74	2.66	1.50
Ranch	10-20	0.41	0.34	0.37	0.030	0.025	0.026	14.0	13.6	14.1	0.31	1.13	0.31	1.23	0.61	0.76
Eden	0-10	1.22	2.13	1.65	0.095	0.073	0.083	13.1 b	29.5 a	19.4 ab	1.61	1.32	0.85	1.56	2.18	2.12
Valley	10-20	0.76	1.09	0.80	0.064	0.049	0.053	12.2	21.6	14.9	1.30 a	0.54 b	0.46 b	0.91	1.10	1.20

	Depth	Nmin mgkg			30d PMN mgkg			% init Nmin as NO3-N			P (Total) %			Olsen-P ppm		
	cm	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**	**AG**	**SI**	**BS**
Succor	0-10	14.77	6.70	11.74	15.64	18.46	22.76	67.1 a	46.5 b	46.7 b	0.072 b	0.130 a	0.144 a	24.9 ab	19.4 b	37.9 a
Creek	10-20	6.56	3.28	5.56	6.99	8.44	10.50	64.6 a	49.5 ab	40.7 b	0.054 b	0.092 a	0.104 a	12.4	10.0	15.6
Lincoln	0-10	5.89	15.31	23.07	15.54	15.31	13.44	45.0 a	8.3 b	10.8 b	0.059	0.052	0.049	34.9	27.2	30.4
Bench	10-20	3.20	5.47	5.78	6.28	6.00	6.12	37.4 a	12.6 b	13.4 b	0.047	0.042	0.038	19.8	11.6	9.0
Cinder Cone	0-10	5.61 a	1.80 b	2.32 b	8.29	6.54	8.24	44.7	30.9	36.6	0.034 a	0.021 b	0.023 b	14.2	13.4	16.0
Butte	10-20	3.38 a	1.33 b	2.08 b	6.31	3.83	4.40	42.6 a	26.9 ab	35.4 b	0.029 a	0.021 ab	0.025 b	8.0 b	11.8 a	13.5 a
Canyon	0-10	2.24	2.37	2.39	4.60	9.14	8.48	14.3	14.5	16.8	0.042	0.034	0.037	19.1	11.1	16.8
Creek	10-20	2.08	1.63	1.53	4.98	4.42	3.04	23.6	21.3	14.4	0.037	0.029	0.030	14.9	7.4	9.4
Vernon	0-10	12.02 a	3.92 b	4.92 b	17.22 a	7.80 b	11.30 ab	86.6 a	74.4 ab	53.5 b	0.084 a	0.067 b	0.067 b	17.1	13.3	14.8
Hills	10-20	4.21	2.63	4.06	4.42	8.46	9.15	75.4 a	52.2 b	48.2 b	0.074 a	0.059 b	0.060 b	7.6	8.6	9.7
Simpson	0-10	4.17	3.22	4.94	4.82 b	4.41 b	11.82 a	64.5	64.2	51.4	0.116 a	0.080 b	0.081 b	10.4	8.5	10.1
Springs	10-20	1.80	2.82	3.40	0.89 b	6.85 a	5.83 a	70.6 a	49.3 b	41.7 b	0.093 a	0.071 b	0.070 b	4.2	5.6	6.2
Izzenhood	0-10	4.14	3.15	1.94	16.97	9.26	14.36	23.3	20.5	23.4	0.046	0.043	0.045	15.4	13.9	19.8
Ranch	10-20	1.53	1.75	1.07	7.12 a	1.98 b	3.25 ab	21.7 b	49.1 a	29.2 ab	0.033	0.025	0.031	6.7	5.1	9.5
Eden	0-10	3.17	3.51	2.98	11.34	13.26	15.27	49.5 a	34.5 ab	26.7 b	0.050	0.044	0.045	15.5	15.3	23.6
Valley	10-20	2.21	1.65	1.67	5.67	8.34	6.55	56.5 a	33.2 b	28.8 b	0.040	0.035	0.034	7.9	5.5	8.8

	Depth	ug/g DTPA Fe						ug/g DTPA Mn					
	cm	**AG**		**SI**		**BS**		**AG**		**SI**		**BS**	
Succor	0-10	13.8	a	9.4	b	6.0	b	38.4	a	12.6	b	9.2	b
Creek	10-20	7.0		5.4		3.8		14.9	a	7.2	ab	4.6	b
Lincoln	0-10	27.9		20.7		21.9		21.8		35.7		42.4	
Bench	10-20	10.6		9.9		8.6		11.4		16.8		20.4	
Cinder Cone	0-10	16.1		14.9		13.8		18.7	a	6.8	b	6.5	b
Butte	10-20	8.0		9.1		8.1		11.4	a	5.4	b	6.0	b
Canyon	0-10	16.1	a	9.6	b	11.2	ab	25.7	a	18.5	b	17.5	ab
Creek	10-20	8.4		6.9		7.0		15.2		15.3		17.3	
Vernon	0-10	2.3		2.1		2.2		5.5		4.3		6.0	
Hills	10-20	1.4	b	1.9	a	2.0	a	3.1	b	3.7	ab	5.3	a
Simpson	0-10	2.1		2.1		2.7		6.2		4.8		8.6	
Springs	10-20	1.5	b	1.8	a	1.7	ab	3.2	b	5.3	ab	7.1	a
Izzenhood	0-10	9.1		6.9		7.8		12.1		9.6		10.5	
Ranch	10-20	3.7		2.6		4.2		5.6		3.6		7.2	
Eden	0-10	9.3		13.0		11.3		12.1	b	20.0	a	14.5	ab
Valley	10-20	4.1	b	6.6	a	5.6	ab	4.6	b	11.3	ab	12.8	a

† AG, annual grass; SI, sagebrush interspace; BS, big sagebrush.

§ Different letters following means within a row and soil attribute denote significant differences at the $P<0.05$ level.

Part II: Moisture Relations of Soils

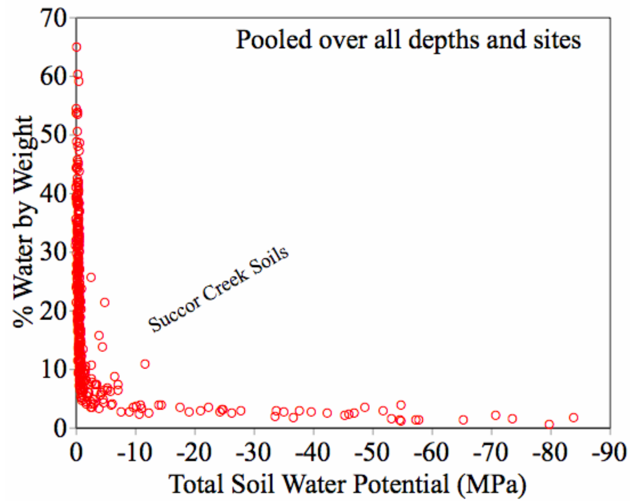

Fig. 4.2. Water release curves for all study sites.

We used the Decagon WP-4 to graph total soil water release curves. The instrument measures the combined effect of osmotic and matric potentials. Two replicate soil samples, 0-20, and 20-40 cm, were collected at each site. The less than 2-mm fraction was used for these tests. Each sample was saturated with deionized water and equilibrated for 24 hours. Samples were inserted in the instrument and readings taken. Samples were then allowed to dry for about 4 hours, were covered and allowed to equilibrate overnight, and readings were taken again. The soils were dried repeatedly and measurements taken for an average of 7 times to obtain a range of soil water contents from saturation to nearly air-dry. Except for the Succor Creek soils, all soils exhibited similar total soil water release curves (**Fig. 4.2**). The Succor Creek soils had much higher clay content than the other soils, which explains its deviation from the other soils. The data show that the energy at which water is held to these soils is remarkably consistent from saturation until slightly less than 10% moisture, at which point the total soil water potential becomes rapidly negative. From a plant root perspective, the energy to obtain water from the soils studies is similar for a large range of soil water contents. We did not expect this asymptotic relationship between water content and total soil water potential. In my laboratory, similar soils were tested on a pressure plate apparatus, which measures only matric potential, and the release curves were much more linear. To produce the results of the study suggests that the osmotic potential must decrease with soil drying (less osmotic potential) to compensate for the increase in matric potential. At this time we lack a plausible explanation for the phenomenon.

Part III: Nutrient Availability

INTRODUCTION

Why has cheatgrass (*Bromus tectorum* L.) become such a problematic weed in the western United States? A plethora of literature has documented fitness traits of cheatgrass that have increased its competitive stature. Among these traits include: rapid growth kinetics (Hulbert, 1955; Harris, 1967), abundant seed production even in drought years (Mack and Pyke, 1983), fall germination when precipitation is adequate (Stuart and Hull, 1949), ability to germinate and establish in a wide variety of seedbed safesites (Young and Evans, 1973; Bookman, 1983), winter hardiness (Hulbert, 1955), rapid water/nutrient uptake kinetics to co-opt from competing species (Melgoza et al., 1990), rapid root elongation to seek out water and nutrients (Harris and Wilson, 1970), and a large positive growth response to elevated atmospheric CO_2 (Smith et al., 1987; Ziska et al., 2005). The balance of these fitness attributes certainly changes depending on specific site conditions and climate, but above all, cheatgrass has displayed an environmental and genetic plasticity that further enhances its competitive ability (Stuart and Hull, 1949).

Greenhouse and field experiments have shown that the invasiveness/competitive stature of many invasive plants is enhanced under high soil nutrient availability and repressed under low soil nutrient availability (Burke and Grime, 1996; Brooks, 2004). The major nutrient that influences the growth rate and invasiveness of cheatgrass is nitrogen; however, in specific circumstances the availability of other nutrients such as phosphorus can be limiting. Field application of a soluble nitrogen salt, can over time lead to encroachment of weedy annual species including cheatgrass into environments that were free of such species (Kay and Evans, 1965; McLendon and Redente, 1991). Conversely, application of labile carbon such as sucrose, which immobilizes nitrogen through microbial uptake, can extirpate weedy annual species in favor of native perennial species (Young et al., 1998; Beckstead and Ausperger, 2004).

It appears then that a potential pathway to restore cheatgrass invaded rangelands involves short and long-term management strategies to control soil nutrient availability. Short-term strategies are necessary to reduce nutrients, particularly available nitrogen, to such a level that appropriate perennial grasses can have a window of opportunity to recruit and compete with nitrophiles such as cheatgrass (Wilson and Gerry, 1995). Long-term strategies involve maintaining soil nutrient availability below a threshold level to perpetuate perennial dominance. Unfortunately, we simply don't know what threshold of nitrogen availability or the magnitude of seasonal variation that encourages cheatgrass to elevate its competitive stature relative to perennial grasses. Moreover, long-term reduction of nutrient availability through sequestration in perennial foliage and litter can be overcome in an instant via nutrient release from soil and plant tissue following a wildfire (Blank et al., 1994).

Labile carbon sources such as sucrose have been used as a short-term strategy to lower nitrogen availability for restoration with some success (Corbin and D'Antonio, 2004), but not universally so (Reever-Morghan and Seastedt, 1999). The theoretical underpinnings are that the soil microbial community is in most cases carbon-limited. Addition of a labile carbon source stimulates microbes. Microbial proliferation results in the sequestration of available forms of nitrogen such as nitrate and ammonium away from plant roots. During this time period of lowered nitrogen availability is a window of opportunity in which restoration is possible. It appears to be a truism that many natives, including perennial grasses, are more nitrogen use efficient (Chapin, 1980). Under conditions of lowered soil nitrogen availability, they can compete with nitrophiles such as cheatgrass. Once these natives become established, they can resist cheatgrass invasiveness by controlling the availability of nutrients at a low level due to sequestration in plant biomass.

The purpose of this research is to obtain greater knowledge of soil nutrient availability in rangeland environments. An experimental design was instituted to evaluate the interactive effects of sucrose addition, plant species, geographical location, soil type, season, and site precipitation on soil nutrient availability. In this team framework, other measurements taken concurrently can be used to statistically evaluate the effect of nutrient availability of attributes ranging from percent cryptogamic cover to plant biomass and density. We chose resin capsules, spherical mesh-covered filled high capacity anion and cation exchangers, to gauge nutrient availability. Resin capsules integrate nutrient availability during the period they are in the soil via diffusion of anions and cations to the resin capsule. We feel that this integrative approach is superior to periodic destructive soil sampling. Moreover, resin capsules more closely approximate true plant availability albeit on a small scale. Resin capsules have been used to quantify availability of NO_3^-, K^+, Ca^{+2}, Mg^{+2}, Fe, Mn, Cu, and Zn.

Working hypotheses include:

1) nutrient availability will be unaffected by sucrose application;
2) nutrient availability will be similar among sites;
3) nutrient availability will be unaffected by season;
4) soil nutrient availability will be similar among different plant species;
5) nutrient availability will be unaffected by site precipitation.

MATERIALS AND METHODS

Hypothesis testing was facilitated by overlaying a resin capsule experiment upon a portion of a robust multi-state experiment. Multiple sites were chosen in 4 states, Utah, Nevada, Idaho, and Oregon.

The commonality of sites was that they were all infested with cheatgrass and often other secondary weeds such as medusahead, mustards, barb-wire Russian thistle. In each state, two sites were chosen to represent average precipitation of between 8 and 10 cm and 10 and 12 cm. For the purpose of the resin capsule study, key treatments included:

1) Herbicide Application – Spring of 2003, Roundup was applied to all plots.
2) Sucrose Application – In the fall of 2003 sucrose was applied at the rate of 1500 kg ha^{-1}. Sucrose was also applied in spring of 2004 at that same rate.

Catagorical variables in this experiment included:

1) Treatment - Sucrose application and control.
2) Sites - Nevada, Utah, Idaho, and Oregon. For the purposes of this report, we did not test for statistical differences between precipitation zones.
3) Seed Mixture – For the purpose of this report, data were pooled over seed mixtures.
4) Measurement Period (season) – Although there was some variation in measurement periods among sites, the following times periods closely approximate:
   - 1^{st} Oct. 2003 through May 2004
   - 2^{nd} May 2004 through Oct. 2004
   - 3^{rd} Oct. 2004 through May 2005
   - 4^{th} May 2005 through Oct. 2005
   - 5^{th} Oct. 2005 through May 2006
   - 6^{th} May 2006 through Oct. 2006 (not included in this report).

Two replicate resin capsules were placed at 15 cm depth in each treatment, site, seed mixture, and measurement period matrix. At the end of each measurement period, resin capsules were exchanged. In the lab, capsules were washed extensively with deionized water and dried. To quantify sorbed anion and cations, capsules were placed in 50 mL polypropylene tubes to which 40 mL of 1N HCl was added and shaken for 1 hour. Tubes were then centrifuged and the clear liquid decanted. Quantification of ortho-P (vanomolybdate chemistry), NH_4^+ (N digestion module-salicylate chemistry), and NO_3^- (N-1-naphthyl-ethylenediamine dihydrochloride chemistry) were done simultaneously using a Lachat flow-injection system. Calcium, Mg^{+2}, Fe, and Mn were quantified using atomic absorption spectroscopy. Potassium and Na^+ were quantified using atomic emission spectroscopy. To make data comparable, values were divided by days resin capsules were in the soil. Because of high blanks for NH_4^+ and generally low values from field measurements, NH_4^+ was not included in statistical analyses.

The experimental design randomized split plot with repeated measures over time. Categorical variables included treatment, site, and season. Data were pooled over seed mixtures. All raw data needed to be log transformed to meet ANOVA assumptions. For significant factors and interactions least square means were compared using the Tukey-Kramer test. For the purpose of this report, we analyzed only NO_3^-, ortho-P, and Mn.

RESULTS AND DISCUSSION

Nitrate

Resin availability of NO_3^- was influenced by significant season x treatment, site x treatment, and site x season interactions **(Table 4.8).** Availability of NO_3^- was greatest during the first measurement period, after herbicide application (**Fig. 4.3**). Sucrose application significantly reduced NO_3^- availability, but only in the first two seasons of measurement (**Fig. 4.3**). Sites responded differently to sucrose application (**Fig. 4.4**). Sucrose application did not

Table 4.8. Results of ANOVA analyses

	NO_3^-	Ortho-P	Mn
Site	<0.0001	<0.0001	<0.0001
Treatment	<0.0001	0.03631	0.0250
Site x Treatment	0.0090	0.1732	0.0106
Season	<0.0001	<0.0001	<0.0001
Site x Season	<0.0001	<0.0001	<0.0001
Treatment x Season	<0.0001	0.0005	0.0522
Site x Treatment x Season	0.0524	0.7044	0.0419

appreciably reduce availability of NO_3^- in either the calcareous Utah soils or the Lincoln Bench soils. Sucrose addition did, however, significantly reduce NO_3^- availability at all other sites with proportional reduction greatest for the Izzenhood site. Sites differed significantly in the magnitude and seasonal availability of NO_3^- (**Fig. 4.5**). Overall, Succor Creek had the greatest resin availability of NO_3^-. All sites except Simpson Springs and Lincoln Bench displayed greatest NO_3^- availability during the first season with declining or variable availability in the following four seasons. Patterns of NO_3^- availability suggest three explanations involving treatment, herbicide application and specific soil condition at individual sites. Sucrose application, in general, significantly reduced the availability of NO_3^- relative to the control treatment. These data support the construct that a labile carbon source causes microbes to proliferate and immobilize N. Indeed, cheatgrass densities and biomass on sucrose-treated plots were much less the first season than control plots (Chapter 7). Moreover, we are presently analyzing cheatgrass tissue for N concentration on sucrose treated and control plots. Once this is done, it will be possibly to relate tissue N concentration with resin N availability and possible determine a threshold of resin N availability to reduce cheatgrass biomass sufficiently to offer the possibility of restoration success. At any rate, it appears that the sucrose effect is short-lived, lasting two seasons. In addition, we did not notice an explosion of N availability as the sucrose effect waned due to mineralization from microbes. This may simply be due to rapid uptake by plant roots and less reaching the resin capsules. Alternatively, the decline in resin N availability with time may reflect sequestration of N in plant litter. The second aspect of resin N availability involves herbicide application. Resin available N was generally greatest in the first season following herbicide application. This finding seems logical given less uptake by plants and more favorable water relations allows greater diffusion of NO_3^- to the resin capsules. Availability of NO_3^- declined in the following measurement seasons likely due to competition of NO_3^- uptake with plant roots and sequestration in plant litter. These data suggest

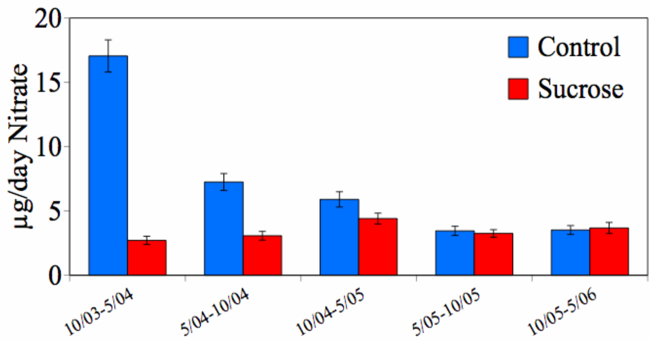

Fig. 4.3. Available nitrate as affected by treatment and season.

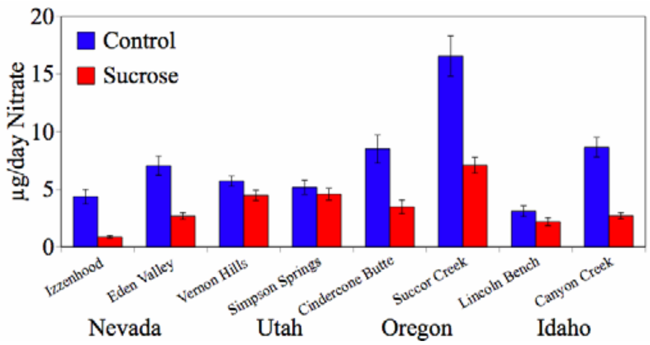

Fig. 4.4. Availability of nitrate as affected by treatment and site.

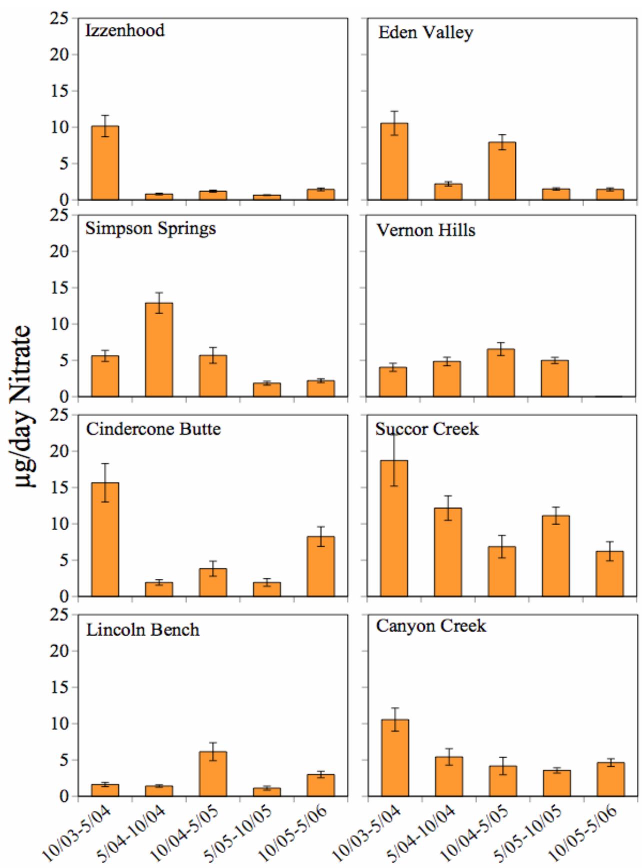

Fig. 4.5. Nitrate availability as affected by site and season.

that herbicide application may temporarily increase nutrient availability and perhaps increase invasion risk. The third important aspect is the large variation in NO_3^- availability and its interaction with treatment among sites. For the Utah sites, sucrose application was ineffective in reducing NO_3^- availability. These sites are calcareous to the soil surface. The presence of free calcium carbonate is known to foster stable Ca-humates which are resistant to mineralization (Duchafour, 1977; Muneer and Oades, 1989). We hypothesize that soil microbes are unlikely to be as stimulated by addition of labile C than the other sites owing to inability to mineralize N from Ca-humate complexes. This speculation is supported by the delayed increase in NO_3^- following herbicide application for the Simpson Spring site.

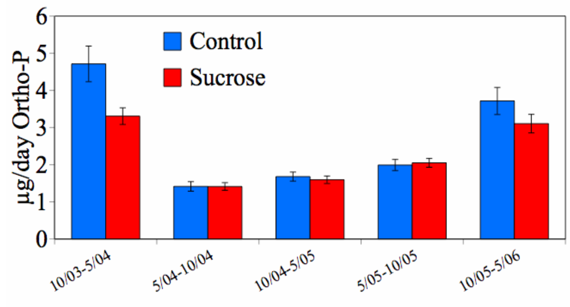

Fig. 4.6. Ortho-P availability as affected by treatment and

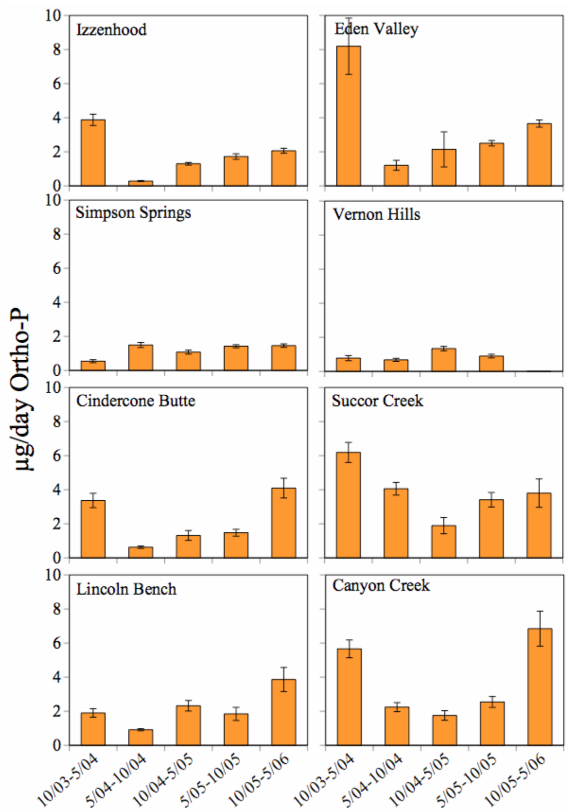

Fig. 4.7. Ortho-P availability as affected by site and season.

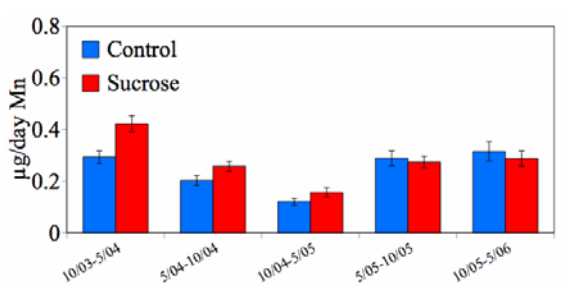

Fig. 4.8. Manganese availability as affected by treatment and season.

Phosphorus

Availability of ortho-P was influenced by significant treatment x season and site x season interactions (**Table 4.8**). After the first season of measurement, overall, sucrose application reduced availability of ortho-P in relation to the control (**Fig. 4.6**). In the following four seasons of measurement, there were no significant differences in availability of ortho-P between sucrose and control treatments. Site and season interacted significantly to affect resin availability of ortho-P (**Fig. 4.7**). Similar to NO_3^- availability, many sites had greatest ortho-P availability the season following herbicide application, with the notable exception of the Utah sites, Lincoln Bench and Canyon Creek. There was a distinct trend for most sites of increasing ortho-P availability with increasing season. Indeed, for the 5th season, Cindercone Butte, Lincoln Bench, and Canyon Creek had their greatest availability of ortho-P. The Utah sites generally had low availability of ortho-P relative to the other sites. We hypothesize that reduction in ortho-P availability, due to sucrose application, is, like NO_3^-, due to microbial immobilization (Chauhan et al., 1981; Schmidt et al., 1999). The magnitude of effect is much less than that for NO_3^-, but perhaps plant growth would also be affected. We are awaiting results of analyses of cheatgrass plant tissue to determine if cheatgrass grown on sucrose plots has less ortho-P concentration than cheatgrass grown on control plots. Similar to patterns for NO_3^-, resin available ortho-P was greatest the season after herbicide application likely due to reduced plant root uptake of ortho-P. Unlike NO_3^-, ortho-P availability increased over the four following seasons. We suspect this is due to increased root exudation of compounds, particularly organic acids, from vegetation to increased ortho-P availability (Jones and Darrah, 1994). Moreover, in an unpublished greenhouse study, the first author measured significantly higher resin available ortho-P for capsules placed in the rooting zone of cheatgrass compared to capsules placed in a similar unplanted soil. That ortho-P availability generally increases with time on the non-calcareous sites also suggests a large capacity of the soil to provide P given the large amount sequestered in plant litter. The Utah sites have far lower resin available ortho-P than the other sites. The literature indicates that high levels of soluble Ca^{+2}, as a consequence of equilibrium with calcium carbonate, results in the formation of stable and insoluble Ca-P phases (Tunesi et al., 1999). One ecological consequence of relatively low availability of ortho-P on the Utah sites is the likelihood of greater importance of plant-mycorrhizal associations to meet plant P requirements (Pfetffer and Bloss, 1988).

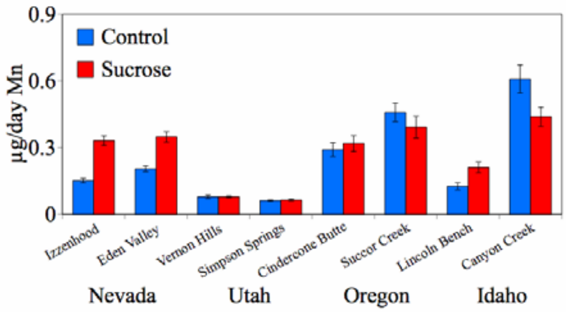

Fig. 4.9. Manganese availability as affected by treatment and

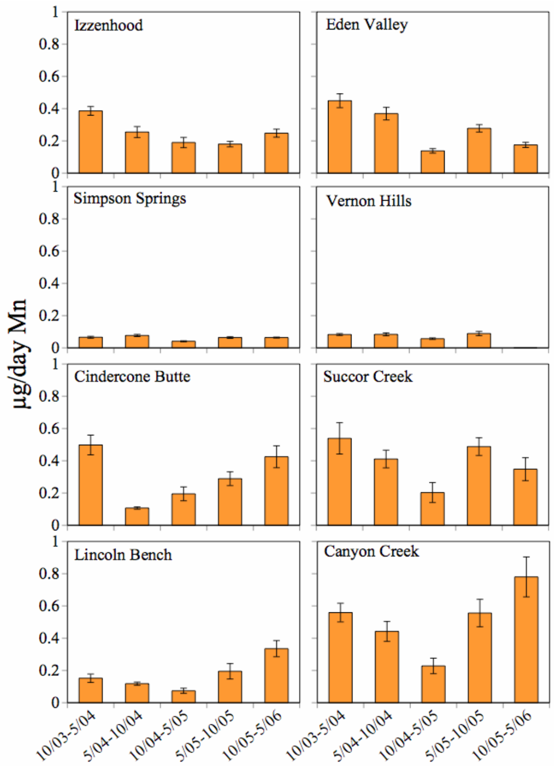

Fig. 4.10. Manganese availability as affected by site and season.

Manganese

Resin available Mn was affected by a slightly significant three-way interaction among treatment, season, and site (**Table 4.8**). For clarity of presentation, we only present the significant and closely significant two-way interactions (**Table 4.8**). Sucrose application increased resin available Mn relative to the controls (**Fig. 4.8**). The magnitude of increase was greatest the first season after herbicide application, but continued through the 3rd season. Treatment effect depended on site (**Fig. 4.9**). The Nevada sites showed the greatest increase in Mn availability upon sucrose application and were the only sites, other than Lincoln Bench, that overall showed an increase in Mn availability with sucrose application (**Fig. 4.9**). Indeed, sucrose application reduced Mn availability for the Canyon Creek site. Sites differed considerably in resin available Mn among seasons (**Fig. 4.10**). The Utah sites had significantly lower resin available Mn than the other sites and availability remained more constant through seasons.

We suspect that the increase in Mn availability upon sucrose application is due to exudation of metal chelators from the flourishing microbial community (Treeby et al., 1989). That the sucrose-mediated increase in Mn availability was site dependent suggests an interaction with local soil characteristics. For the Utah sites, the lack of a response in Mn availability with sucrose application may be due to the presence of free calcium carbonate. As was eluded to above, highly stable Ca-humate complexes occur in soils with free calcium carbonate. These complexes may resist mineralization and thus constrain the expected microbial explosion upon sucrose addition resulting in lower exudation of chelators. Calcium carbonate has been shown to decrease the availability of Mn (Dahiya and Singh, 2004) and in general solubility of Mn declines at alkaline pH (Lindsay, 1979), which explains why the Utah sites have lower Mn availability. It is difficult to discern the ecological significance of our data because, to our knowledge, resin available Mn has never been related to a plant available pool such as a DPTA extract. Moreover, there is limited information of optimal plant requirements in wild plants. None-the-less, given the importance of Mn in the water-splitting reaction in photosynthesis and electron transport (Marschner, 1995), the large differences in resin availability among sites, among seasons, and with sucrose addition on some sites, may influence plant growth in some instances.

SUMMARY AND FUTURE DIRECTION

The key findings of this research are: 1) sucrose addition can reduce NO_3^- and ortho-P availability, but soil characteristics affect the process; 2) herbicide application results in a general increase in soil nutrient availability; 3) application of sucrose can also increase the availability of nutrients such as Mn. We are in the process of analyzing the last resin set. When this is completed, we will statistically analyze all nutrient data and ask more detailed questions of the data set. Such questions would include: 1) does nutrient availability differ between spring-summer and fall-winter?; 2) does seeding regime affect nutrient availability?; 3) does the availability of particular nutrient pairs correlate and what is the significance?. Furthermore, the resin capsule data set, when combined with other site data, particularly the analysis of tissue samples of cheatgrass taken concurrently with resin capsule measurements, should allow one to relate nutrient availability to plant growth/density measurements and deduce nutrient factors affecting cheatgrass growth and competitiveness.

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Chapter 5 – Experiment 1: Screening native cultivars as a transition community

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INTRODUCTION

Developing concepts and management strategies to reduce the dominance of cheatgrass (*Bromus tectorum* L.) and other weeds on Great Basin rangelands is greatly needed. These invasive weeds have disrupted wildfire regimes and greatly modified the structure and function of plant communities. Most noticeable is the loss of native species diversity including the fire-intolerant big sagebrush species (*Artemisia tridentata* Nutt.) and the herbaceous understory of perennial grasses and forbs. Restoring these native plant communities requires the identification of promising native plant materials that can be used for transition once cheatgrass dominance has been reduced (Westoby et al 1989, Chambers 2000).

Many native and introduced grass species from numerous functional groups are available for restoration purposes. Promising native early-seral, short-lived perennial grasses from the bluegrass (*Poa secunda* ssp. *secunda* and *P secunda* ssp. *juncifolia)* and squirreltail (*Elymus elymoides* [Raf.] Swezey and *E. multisetus* [J.G. Smith] Burtt-Davy) complexes are available for restoration (Kellogg 1985, Jones 1998). These complexes are broadly distributed and occupy a wide variety of semiarid environments throughout temperate western North America ranging from desert to subalpine (Wilson 1963, Patterson et al. 2005). Bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] A. Löve), Snake River wheatgrass (*Elymus wawawaiensis* J. Carlson & Barkworth), and basin wildrye (*Leymus cinereus* [Scribn. & Merr.] A. Löve) are long-lived perennial bunchgrasses. Bluebunch wheatgrass and basin wildrye are broadly distributed in western North America and the Great Basin (Miller et al. 1986), while Snake River wheatgrass is confined to the lower Salmon, Snake, and Columbia River drainages of the Pacific Northwest (Jones et al. 1991). Rhizomatous perennial grasses, including thickspike (*Elymus lanceolatus* [Scribn. & J.G. Sm.] Gould and western wheatgrass (*Pascopyrum smithii* [Rydb.] A. Löve), are a third functional group of native grasses available for restoration in the Great Basin. These three native perennial grass groups may perform differently when competing with invasive annual grasses on disturbed Great Basin rangelands.

Transitioning annual-dominated communities of the Great Basin to perennial vegetation may also be facilitated by using introduced species that have proven to be effective in stabilizing overgrazed areas (Asay et al. 2001, Cox and Anderson 2004). Annual sterile cereal grasses are a mainstay of revegetation on steep forested slopes, but they have also gained attention for weed control (Moyer et al 2000) and restoration of fire-prone ecosystems (Beyers 2004). Sterile cereals present an attractive alternative for restoration if their rapid early-season growth can reduce the productivity of cheatgrass without hampering native species establishment in subsequent years. In contrast, long-lived introduced forage grasses like crested wheatgrass and Siberian wheatgrass also quickly establish and may facilitate the establishment of native perennial grasses when planted simultaneously (Waldron et al. 2005). Thus, annual and perennial introduced grass species may be used to complement direct seeding of native perennial grass species.

The overall objective of this study is to identify promising plant materials to use to transition from cheatgrass dominance to a diverse, native plant community. Here we report on 21 promising accessions of grasses and a few forbs and shrubs planted on 8 sites in the Great Basin to determine success of establishment when seeded in two successive years. This information will identify plant materials capable of maintaining stands two years after seeding.

MATERIALS AND METHODS

Study Sites

Research sites were chosen in 4 states: Utah, Nevada, Idaho, and Oregon. All sites were dominated by cheatgrass and often other secondary weeds such as medusahead, wildrye, mustards, and Russian thistle. Two sites were chosen in each state to represent average annual precipitation of between 8 and 10 inches (low) and 10 and 12 inches (high). Replicated plot plantings were established using the Truax drill in autumn of 2003 and 2004 at two locations in each of the states (**Table 5.1**) to evaluate different cultivars for their competitive ability with cheatgrass.

Table 5.1 Seeding dates for Experiment 1 at each study site

State	Study site	2003 seeding dates	2004 seeding dates
Idaho	Canyon Creek (high)	October 20-21	October 20-21
	Cinder Cone Butte (low)	October 21-22	October 21-22
Nevada	Eden Valley (high)	November 10-11	October 27-28
	Izzenhood Ranch (low)	November 12-13	October 29-30
Oregon	Lincoln Bench (high)	October 27-28	October 24-25
	Succor Creek (low)	October 29-30	October 25-26
Utah	Simpson Springs (low)	November 3-4	October 18-19
	Vernon Hills (high)	November 5-6	October 17-18

This experiment included eight separate plantings in 2003 and eight more in 2004. Seed for Experiment 1 was purchased from seed companies or supplied by NRCS, ARS, or the USFS.

Seeded Species

The following 21 accessions were seeded at all sites in all states: bluebunch wheatgrass (Anatone, P-12, Goldar, and P-7), Snake River wheatgrass (Secar and SERDP), Sandberg bluegrass (Hanford, High Plains, Mountain Home and Sherman), thickspike wheatgrass (Bannock and Critana), squirreltail (Sand Hollow and Shaniko Plateau), crested wheatgrass (CD II and Vavilov), sterile wheat hybrids (Pioneer, Regreen and Stani), mountain wildrye, and scarlet globemallow. Details of seed sources are provided in Chapter 2.

Experimental Design

At each study site, 6 blocks of 25 plots (accessions) were established for each of the 2 seeding years using a randomized complete block design (Chapter 1). Plots were arranged as a split-plot design with herbicide treatments as whole plots and accessions as split plots. Three blocks were treated with herbicide to remove cheatgrass and provide a control reference. The remaining three blocks were not treated and cheatgrass was allowed to grow and compete with each seeded accession to assess its competitive ability. Each block was surrounded by a 50' buffer strip. Each plot was 10' x 20' and consisted of 10 rows of an accession, with each row 20' long and spaced 1' apart. Individual plots had minimal spacing between adjacent plots, and the plots on the outside of the block had a 10' buffer to the edge of the block. Herbicide treatments consisted of a spring treatment of Rodeo/Roundup and follow-up spot treatments as needed. Herbicide was applied to the entire treated block, *i.e.*, an area of 70' x 120' for each of 3 blocks in each of 2 years at each study area, or a total of ~0.6 acres each year per study area for Experiment 1.

Experimental Variables

Plant density of seeded species, cheatgrass, and other species (pooled) was measured with a 3' x 3' steel frame (**Fig. 5.1**) placed in four random, non-overlapping locations within a subplot with the center of the frame centered on the drill rows. The outer two feet of each plot was not included in the sampled area. The frame (quadrat) was divided into 9 1-ft^2 sections. Density was measured in three (shaded) of the nine sections. Quadrats were placed in the same location for all sampling dates. Two corners of the quadrat were permanently marked with wire flags. This facilitated placement of the metal frame in the same location at every census and helped personnel avoid stepping in the quadrat area.

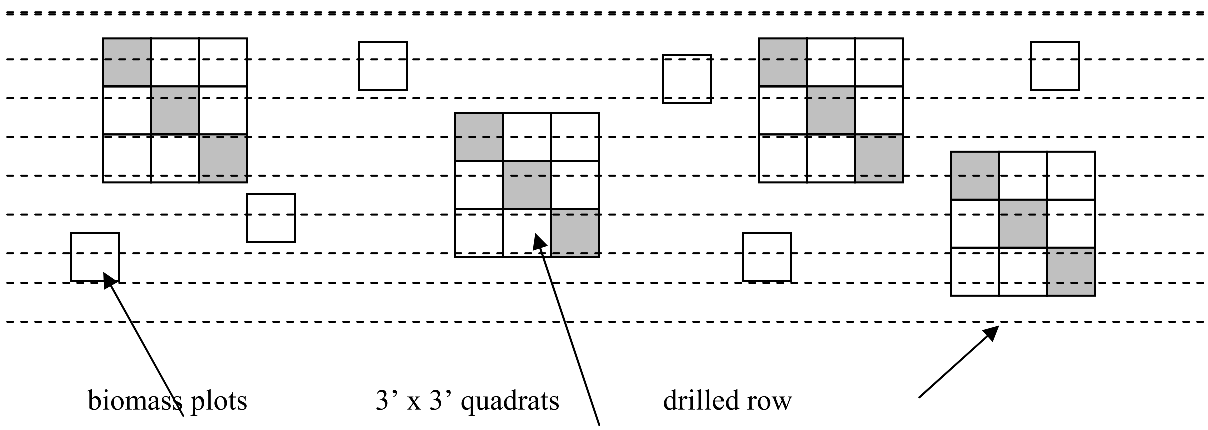

Fig. 5.1. Density and biomass plot arrangement.

On some occasions, only 1, 4, or 9-in^2 sections of the 1-ft^2 sub-quadrats were used to determine cheatgrass and other species density. This was accomplished by placing thin metal rods on these marks to form these smaller sections. The small 1-in^2 was often used when cheatgrass was extremely dense. The 9-in^2 area was used on sites where cheatgrass had a lower density.

Biomass of seeded species, cheatgrass, and all other species was measured for six 1-ft^2 sections centered on a drilled row. These were randomly selected at the first sampling date in the first year of sampling. Plots were clipped to remove all aboveground biomass at the time of peak biomass in three quadrats in the first and second year after seeding. Biomass samples were bagged, dried to constant weight, separated into the three species categories, and then weighed to determine dry mass.

RESULTS AND DISCUSSION

The 2003 and 2004 seedings experienced high seedling mortality during their first respective growing seasons. Consequently, the second census reflects low numbers, but provides a good assessment of the ability of species and accessions to persist under the inevitably harsh conditions of summer aridity. This chapter does not attempt to relate seedling establishment success with key functional differences (*e.g.*, climate, soils, and rangeland management history) between the eight sites. Instead, we focus on 1) identifying general patterns of seedling density over time when accessions within a species are combined and 2) distinguishing differences between accessions within a species. Finally, we provide insights into the main effects of the herbicide treatment at each of the eight sites.

Change in Density Over Time for 2003 Seedings

Establishment and persistence into 2005 were generally negligible except at Simpson Springs, UT and Izenhood Ranch and Eden Valley, NV (**Table 5.2 and 5.4**). In contrast, the Idaho sites and Succor

Creek, Oregon failed to support any perennial seedlings in the 2005 census. Surprisingly, the low-precipitation Utah site (Simpson Springs) had generally greater seedling survival than the high-precipitation site (Vernon Hills).

The cereals successfully established at all sites with the exception of Cinder Cone Butte in Idaho. As anticipated they failed to recruit new individuals and had few seedlings present in 2005, except at Simpson Springs in Utah and Lincoln Bench in Idaho. Western yarrow initially established at Simpson Springs, Utah and Eden Valley, Nevada, but did not persist until 2005. In most cases fewer crested wheatgrass seedlings were found as the season progressed in 2004; however, density increased during 2004 at both Oregon sites. Crested wheatgrass maintained seedlings into 2005 at Lincoln Bench, Oregon and the Utah and Nevada sites, particularly at Simpson Springs and Eden Valley.

Squirreltail seedlings persisted only at the Utah and Nevada sites and Lincoln Bench in Oregon. Squirreltail establishment in 2004 was higher at the high-precipitation Idaho site (Cinder Cone Butte) than the low-precipitation site (Canyon Creek). No squirreltail seedlings were observed at either Idaho site or Succor Creek, Oregon in 2005, and few were observed at Lincoln Bench, Oregon or Vernon Hills, Utah. Thickspike, Snake River, and bluebunch wheatgrasses, as well as basin wildrye and bluegrass, had similar establishment and survival patterns across all 8 sites. All of these grasses did well at the successful sites (Simpson Springs, Utah and both Nevada sites) and maintained low, but viable densities at Lincoln Bench, Oregon. Globemallow appeared on a few sparse occasions across the eight sites, but did not maintain seedlings into 2005.

Change in Density Over Time for 2004 Seedings

In general, the 2004 seedings had much greater success than the 2003 seedlings (**Table 5.3 and 5.5**). Similar to the 2003 seedings, establishment and survival was consistently greater for all species at the Utah and Nevada sites than the Idaho and Oregon sites. Canyon Creek, Idaho had much lower overall seedling density than the other seven sites.

The cereals had particularly high establishment in 2005 at Lincoln Bench and the Utah sites. They maintained seedlings into 2006 at all sites except Succor Creek, Oregon and Izzenhood Ranch, Nevada. Unlike the 2003 seedings, western yarrow established well at Lincoln Bench, Oregon, Vernon Hills, Utah, and Eden Valley, Nevada. Nevertheless, few yarrow seedlings were found by the second 2005 census. The seven perennial grass species established fairly well in 2005 except at Canyon Creek, Idaho. Similar to the 2003 seedings, seedling persistence into 2006 was consistently better at the Utah and Nevada sites. In contrast to the 2003 seedings, most of the perennial grasses had seedlings survive into 2006. In most cases, seeding density of perennial grasses steadily declined from the early census in 2005 until the final census in 2006.

Herbicide, Entry, and Interaction Effects

Herbicide treatment generally had little impact on species density, especially for the 2003 seedings. For the 2003 seedings, a positive effect of herbicide treatment was detected at Izzenhood Ranch, Nevada at the second and third censuses in 2004. A negative effect was detected at Canyon Creek, Idaho at all three censuses in 2004. For the 2004 seedings, herbicide treatment increased seedling density at Idaho and Oregon sites and Simpson Springs, Utah at the first census and at Eden Valley, Nevada at the second census.

Differences among accessions for seedling density were present for all 16 seedings except the two 2003 Idaho seedings. Interaction between herbicide treatment and accessions was fairly common despite general nonsignificance of the treatment main effect. For the 2003 seedings, an interaction was present at Cinder Cone Butte, Idaho for all three censuses; both Oregon sites and Izzenhood Ranch, Nevada for the second and third censuses; and Vernon Hills, Utah for the third census. No interactions were seen for 2003 seedings for Canyon Creek, Idaho; Simpson Springs, Utah; or Eden Valley, Nevada. For 2004 seedings, an interaction was present at both census for Canyon Creek, Idaho and Simpson Springs, Nevada. Interactions were also present at the first census only for Lincoln Bench, Oregon and Eden Valley, Nevada and at the second census only for Succor Creek, Oregon.

Comparisons of Accessions within Species

Comparisons were made among accessions in the same species group for all censuses the year after seeding. CD II crested wheatgrass was superior in 14 of 40 comparisons, and Vavilov was superior in none. Shaniko Plateau squirreltail was superior in 10 of 40 comparisons, and Sand Hollow was superior in 2. Critana thickspike wheatgrass was superior in 12 of 40 comparisons, and Bannock was superior in none. SRDP Snake River wheatgrass was superior in 5 of 40 comparisons, and Secar was superior in 1. Trailhead was superior in 2 of 35 comparisons, and Magnar was superior in none. Based on extreme high or low position over all comparisons, rank of bluegrasses was Sherman (highest), High Plains, Mountain Home, and Hanford (lowest). Overall rank of bluebunch wheatgrasses was Anatone (highest), P-12, P-7, and Goldar (lowest). Mountain rye outperformed the other cereals, which were relatively similar to one another.

Accessions Performing Better than Crested Wheatgrass

The crested wheatgrass accession CD II (*A. desertorum* x *A. cristatum*) generally performed better than Vavilov (*A. fragile*). Therefore, we used CD II as a benchmark to identify superior accessions. For the 2003 seedings, accessions with greater seedling density than CD II in 2004 were found at all sites except Simpson Springs, Utah (**Table 5.2**). However, most of the superior accessions were cereals. Anatone was superior for the first and third census at Vernon Hills, Utah and for the second census at Lincoln Bench, Oregon and Izzenhood Ranch, Nevada. P-12 was superior for the second and third censuses at Lincoln Bench, Oregon. P-7 and Critana were superior for the second census at Lincoln Bench, Oregon and Eden Valley, Nevada, respectively.

For the 2004 seedings, accessions with greater seedling density than CD II in 2005 were found at all sites except the Nevada sites (**Table 5.3**). Again, most of the superior accessions were cereals. Anatone was superior to CD II for the first census at Simpson Springs, Utah. SRDP, Secar, Critana, Anatone, and P-12 were superior for the second census at Lincoln Bench, Oregon.

Table 5.2. Means and standard errors of plant density for plants seeded in 2003.

CHANGE IN DENSITY OVER TIME: 2003 SEEDINGS

	ID/CCK	s.e.	ID/CCB	s.e.	OR/LB	s.e.	OR/SC	s.e.	UT/VH	s.e.	UT/SS	s.e.	NV/EV	s.e.	NV/IR	s.e.
HR TRT: 1st census/2004	**0.05**	0.02	**1.03**	0.10	**0.49**	0.07	**0.36**	0.05	**0.60**	0.06	**2.98**	0.17	**1.02**	0.12	**2.97**	0.17
HR TRT: 2nd census/2004	**0.08**	0.02	**0.69**	0.07	**0.77**	0.08	**0.64**	0.06	**0.32**	0.05	**2.56**	0.14	**0.44**	0.07	**1.82**	0.13
HR TRT: 3rd census/2004	**0.10**	0.02	**0.59**	0.06	**1.22**	0.09	**0.59**	0.07	**0.16**	0.03	**1.83**	0.11	**0.56**	0.08	**1.74**	0.11
HR TRT: 1st census/2005	**0.00**	0.00	**0.02**	0.01	**0.19**	0.03	**0.02**	0.01	**0.02**	0.01	**0.83**	0.06	**0.38**	0.06	**0.62**	0.07
HR TRT: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.34**	0.06	**0.00**	0.00	**0.15**	0.03	**0.85**	0.06	**0.44**	0.05	**0.30**	0.04
NH TRT: 1st census/2004	**0.60**	0.11	**0.08**	0.03	**0.43**	0.07	**0.32**	0.05	**0.66**	0.09	**3.27**	0.19	**1.19**	0.14	**2.70**	0.16
NH TRT: 2nd census/2004	**0.52**	0.08	**0.06**	0.02	**0.48**	0.07	**0.41**	0.06	**0.46**	0.06	**2.63**	0.13	**0.22**	0.06	**0.88**	0.10
NH TRT: 3rd census/2004	**0.45**	0.06	**0.11**	0.03	**0.62**	0.07	**0.40**	0.06	**0.14**	0.04	**1.89**	0.11	**0.29**	0.06	**0.76**	0.08
NH TRT: 1st census/2005	**0.00**	0.00	**0.01**	0.01	**0.03**	0.01	**0.01**	0.01	**0.00**	0.00	**0.92**	0.08	**0.33**	0.05	**0.29**	0.04
NH TRT: 2nd census/2005	**0.00**	0.00	**0.01**	0.01	**0.11**	0.02	**0.01**	0.01	**0.02**	0.01	**0.87**	0.06	**0.84**	0.09	**0.07**	0.02
Cereals: 1st census/2004	**2.03**	0.30	**0.66**	0.15	**2.70**	0.20	**1.84**	0.16	**1.54**	0.26	**4.51**	0.36	**1.20**	0.26	**5.46**	0.36
Cereals: 2nd census/2004	**1.84**	0.23	**0.56**	0.12	**2.88**	0.21	**2.11**	0.18	**1.19**	0.19	**3.81**	0.29	**0.65**	0.17	**3.72**	0.27
Cereals: 3rd census/2004	**1.69**	0.17	**0.53**	0.10	**2.55**	0.18	**2.02**	0.18	**0.61**	0.12	**2.94**	0.18	**0.65**	0.16	**3.10**	0.19
Cereals: 1st census/2005	**0.00**	0.00	**0.01**	0.01	**0.28**	0.08	**0.01**	0.01	**0.00**	0.00	**0.47**	0.10	**0.01**	0.01	**0.01**	0.01
Cereals: 2nd census/2005	**0.00**	0.00	**0.03**	0.02	**0.88**	0.19	**0.03**	0.02	**0.08**	0.05	**0.43**	0.07	**0.01**	0.01	**0.02**	0.01
Yarrow: 1st census/2004	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.12**	0.07	**0.13**	0.07		
Yarrow: 2nd census/2004	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.03**	0.02	**0.05**	0.04		
Yarrow: 3rd census/2004	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.01**	0.01	**0.10**	0.10		
Yarrow: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00		
Yarrow: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00		
CWG: 1st census/2004	**0.00**	0.00	**0.83**	0.24	**0.07**	0.05	**0.11**	0.05	**0.63**	0.15	**3.72**	0.52	**1.88**	0.54	**2.90**	0.31
CWG: 2nd census/2004	**0.00**	0.00	**0.42**	0.16	**0.08**	0.05	**0.60**	0.11	**0.25**	0.08	**2.61**	0.32	**0.30**	0.22	**0.94**	0.25
CWG: 3rd census/2004	**0.00**	0.00	**0.46**	0.17	**0.74**	0.18	**0.58**	0.11	**0.11**	0.05	**2.39**	0.27	**0.59**	0.24	**1.21**	0.24
CWG: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.13**	0.04	**0.00**	0.00	**0.04**	0.03	**1.64**	0.19	**0.43**	0.14	**0.64**	0.14
CWG: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.14**	0.05	**0.00**	0.00	**0.18**	0.06	**1.68**	0.22	**1.29**	0.20	**0.39**	0.10
SQT: 1st census/2004	**0.00**	0.00	**0.40**	0.13	**0.10**	0.04	**0.08**	0.04	**0.06**	0.04	**2.38**	0.27	**1.24**	0.32	**2.11**	0.38
SQT: 2nd census/2004	**0.01**	0.01	**0.26**	0.09	**0.17**	0.04	**0.25**	0.06	**0.13**	0.05	**1.96**	0.25	**0.24**	0.14	**1.26**	0.33

SQT: 3rd census/2004	**0.01**	0.01	**0.18**	0.07	**0.66**	0.13	**0.18**	0.06	**0.00**	0.00	**1.47**	0.23	**0.23**	0.14	**1.08**	0.22
SQT: 1st census/2005	**0.01**	0.01	**0.00**	0.00	**0.01**	0.04	**0.00**	0.00	**0.00**	0.00	**1.26**	0.32	**0.46**	0.14	**0.18**	0.05
SQT: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.11**	0.04	**0.00**	0.00	**0.04**	0.03	**0.92**	0.13	**0.85**	0.26	**0.08**	0.04
TSWG: 1st census/2004	**0.00**	0.00	**0.72**	0.24	**0.00**	0.00	**0.00**	0.00	**0.44**	0.10	**3.89**	0.56	**1.08**	0.19	**2.89**	0.38
TSWG: 2nd census/2004	**0.01**	0.01	**0.75**	0.23	**0.07**	0.04	**0.24**	0.10	**0.22**	0.07	**3.31**	0.41	**0.57**	0.14	**1.46**	0.36
TSWG: 3rd census/2004	**0.00**	0.00	**0.67**	0.15	**0.58**	0.18	**0.08**	0.03	**0.03**	0.02	**2.71**	0.35	**0.69**	0.15	**1.97**	0.43
TSWG: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.10**	0.04	**0.00**	0.00	**0.00**	0.00	**0.89**	0.12	**0.21**	0.06	**0.25**	0.09
TSWG: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.06**	0.04	**0.00**	0.00	**0.12**	0.06	**0.97**	0.13	**1.10**	0.22	**0.15**	0.04
SRWG: 1st census/2004	**0.00**	0.00	**0.94**	0.24	**0.01**	0.01	**0.18**	0.11	**0.69**	0.11	**5.07**	0.50	**1.78**	0.34	**3.65**	0.39
SRWG: 2nd census/2004	**0.04**	0.02	**0.76**	0.18	**0.47**	0.17	**0.64**	0.16	**0.49**	0.11	**4.38**	0.35	**0.36**	0.11	**1.39**	0.27
SRWG: 3rd census/2004	**0.01**	0.01	**0.74**	0.19	**1.31**	0.24	**0.75**	0.22	**0.04**	0.03	**3.21**	0.28	**0.76**	0.23	**1.05**	0.18
SRWG: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.08**	0.04	**0.00**	0.00	**0.03**	0.02	**1.89**	0.19	**0.15**	0.05	**0.14**	0.05
SRWG: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.14**	0.06	**0.00**	0.00	**0.06**	0.03	**1.72**	0.15	**0.69**	0.29	**0.14**	0.05
BWR: 1st census/2004	**0.00**	0.00	**0.72**	0.21	**0.00**	0.00	**0.00**	0.00	**0.44**	0.10	**3.97**	0.49	**0.57**	0.17		
BWR: 2nd census/2004	**0.00**	0.00	**0.39**	0.13	**0.18**	0.08	**0.03**	0.02	**0.10**	0.05	**3.06**	0.35	**0.17**	0.12		
BWR: 3rd census/2004	**0.00**	0.00	**0.22**	0.08	**0.94**	0.21	**0.04**	0.03	**0.00**	0.00	**1.51**	0.20	**0.17**	0.14		
BWR: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.01**	0.01	**0.00**	0.00	**0.00**	0.00	**0.51**	0.09	**0.53**	0.21		
BWR: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.07**	0.04	**0.00**	0.00	**0.01**	0.01	**0.71**	0.11	**0.85**	0.17		
BG: 1st census/2004	**0.00**	0.00	**0.37**	0.10	**0.02**	0.02	**0.00**	0.00	**0.17**	0.05	**1.99**	0.20	**1.03**	0.20	**2.55**	0.26
BG: 2nd census/2004	**0.00**	0.00	**0.11**	0.04	**0.03**	0.02	**0.03**	0.01	**0.08**	0.03	**1.72**	0.16	**0.07**	0.03	**0.12**	0.06
BG: 3rd census/2004	**0.02**	0.02	**0.09**	0.03	**0.03**	0.02	**0.03**	0.01	**0.01**	0.01	**0.59**	0.09	**0.08**	0.03	**0.13**	0.06
BG: 1st census/2005	**0.00**	0.00	**0.07**	0.04	**0.07**	0.03	**0.07**	0.04	**0.01**	0.01	**0.53**	0.10	**0.78**	0.11	**1.55**	0.18
BG: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.20**	0.06	**0.00**	0.00	**0.19**	0.06	**0.56**	0.09	**0.95**	0.15	**0.59**	0.12
BBWG: 1st census/2004	**0.00**	0.00	**0.63**	0.17	**0.06**	0.04	**0.09**	0.05	**1.08**	0.15	**3.41**	0.29	**1.31**	0.20	**3.47**	0.27
BBWG: 2nd census/2004	**0.01**	0.01	**0.40**	0.10	**0.52**	0.11	**0.28**	0.08	**0.57**	0.13	**2.93**	0.25	**0.53**	0.15	**1.58**	0.21
BBWG: 3rd census/2004	**0.00**	0.00	**0.37**	0.08	**1.06**	0.14	**0.24**	0.07	**0.22**	0.06	**2.45**	0.20	**0.64**	0.15	**1.45**	0.16
BBWG: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.13**	0.04	**0.00**	0.00	**0.03**	0.02	**1.35**	0.12	**0.53**	0.12	**0.16**	0.04
BBWG: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.08**	0.03	**0.00**	0.00	**0.04**	0.02	**1.40**	0.13	**0.64**	0.13	**0.07**	0.02
GM: 1st census/2004	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.10**	0.07	**0.00**	0.00
GM: 2nd census/2004	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.03**	0.03	**0.08**	0.05	**0.00**	0.00	**0.00**	0.00

GM: 3rd census/2004	**0.00**	0.00	**0.25**	0.14	**0.00**	0.00	**0.00**	0.00	**0.03**	0.03	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00
GM: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.03**	0.03	**0.06**	0.04	**0.00**	0.00	**0.06**	0.04
GM: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00

Table 5.3. Means and standard errors of plants seeded in 2004.

CHANGE IN DENSITY OVER TIME: 2004 SEEDINGS

	ID/CCK	s.e.	ID/CCB	s.e.	OR/LB	s.e.	OR/SC	s.e.	UT/VH	s.e.	UT/SS	s.e.	NV/EV	s.e.	NV/IR	s.e.
HR TRT: 1st census/2005	**0.51**	0.07	**1.36**	0.10	**1.75**	0.17	**1.36**	0.10	**3.01**	0.20	**4.43**	0.26	**1.58**	0.11	**4.05**	0.22
HR TRT: 2nd census/2005	**0.56**	0.07	**1.54**	0.12	**2.87**	0.18	**1.54**	0.12	**2.77**	0.19	**5.12**	0.25	**1.92**	0.13	**4.40**	0.26
HR TRT: 1st census/2006	**0.17**	0.05	**0.51**	0.13	**0.59**	0.24	**0.19**	0.04	**0.66**	0.07	**0.51**	0.06	**0.65**	0.19	**0.69**	0.18
HR TRT: 2nd census/2006	**0.11**	0.03	**0.37**	0.05	**0.17**	0.03	**0.02**	0.01	**0.65**	0.07	**0.80**	0.07	**0.30**	0.06	**0.37**	0.10
NH TRT: 1st census/2005	**0.68**	0.11	**0.87**	0.08	**1.36**	0.17	**0.87**	0.08	**3.00**	0.21	**2.84**	0.22	**2.08**	0.14	**4.00**	0.22
NH TRT: 2nd census/2005	**0.68**	0.10	**1.08**	0.09	**2.39**	0.18	**1.08**	0.09	**2.42**	0.17	**4.80**	0.25	**2.65**	0.16	**3.81**	0.23
NH TRT: 1st census/2006	**0.02**	0.01	**0.14**	0.03	**0.05**	0.01	**0.09**	0.03	**0.10**	0.02	**0.36**	0.06	**1.25**	0.23	**0.54**	0.17
NH TRT: 2nd census/2006	**0.00**	0.00	**0.14**	0.03	**0.01**	0.00	**0.04**	0.02	**0.54**	0.05	**0.64**	0.07	**0.26**	0.05	**0.16**	0.03
Cereals: 1st census/2005	**3.72**	0.29	**3.43**	0.21	**7.03**	0.39	**3.43**	0.21	**8.60**	0.47	**10.95**	0.48	**3.31**	0.30	**3.45**	0.37
Cereals: 2nd census/2005	**3.73**	0.26	**3.93**	0.22	**7.67**	0.42	**3.93**	0.22	**6.72**	0.44	**10.71**	0.45	**4.58**	0.40	**4.82**	0.51
Cereals: 1st census/2006	**0.47**	0.17	**0.16**	0.04	**0.08**	0.05	**0.01**	0.01	**0.27**	0.09	**0.14**	0.07	**1.01**	0.64	**0.03**	0.02
Cereals: 2nd census/2006	**0.17**	0.07	**0.28**	0.08	**0.11**	0.04	**0.00**	0.00	**0.55**	0.11	**0.60**	0.12	**0.00**	0.00	**0.03**	0.02
Yarrow: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.36**	0.10	**0.00**	0.00	**0.00**	0.00	**0.14**	0.14	**0.98**	0.37		
Yarrow: 2nd census/2005	**0.01**	0.01	**0.00**	0.00	**0.82**	0.21	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**1.14**	0.35		
Yarrow: 1st census/2006	**0.03**	0.03	**0.00**	0.00	**0.29**	0.12	**0.01**	0.01	**0.00**	0.00	**0.01**	0.01	**0.00**	0.00		
Yarrow: 2nd census/2006	**0.01**	0.01	**0.00**	0.00	**0.00**	0.00	**0.01**	0.01	**0.08**	0.04	**0.11**	0.05	**0.06**	0.03		
CWG: 1st census/2005	**0.00**	0.00	**1.36**	0.18	**0.32**	0.11	**1.36**	0.18	**2.38**	0.27	**3.10**	0.47	**1.76**	0.25	**6.68**	0.61
CWG: 2nd census/2005	**0.00**	0.00	**1.58**	0.24	**1.75**	0.28	**1.58**	0.24	**2.39**	0.30	**4.58**	0.46	**2.40**	0.36	**6.79**	0.61
CWG: 1st census/2006	**0.01**	0.01	**1.14**	0.49	**0.06**	0.03	**0.03**	0.02	**0.67**	0.16	**0.38**	0.13	**0.65**	0.16	**0.47**	0.13
CWG: 2nd census/2006	**0.04**	0.04	**1.15**	0.24	**0.15**	0.06	**0.00**	0.00	**0.63**	0.13	**0.58**	0.12	**0.60**	0.22	**0.94**	0.28
SQT: 1st census/2005	**0.00**	0.00	**0.43**	0.13	**0.26**	0.08	**0.43**	0.13	**1.25**	0.19	**1.11**	0.23	**1.26**	0.22	**2.81**	0.34
SQT: 2nd census/2005	**0.01**	0.01	**0.74**	0.18	**0.92**	0.15	**0.74**	0.18	**1.74**	0.21	**2.88**	0.28	**2.17**	0.25	**3.32**	0.38
SQT: 1st census/2006	**0.03**	0.02	**0.10**	0.04	**0.24**	0.08	**0.00**	0.00	**0.33**	0.10	**0.29**	0.09	**0.67**	0.13	**0.18**	0.14
SQT: 2nd census/2006	**0.06**	0.06	**0.33**	0.11	**0.24**	0.08	**0.07**	0.04	**0.63**	0.13	**0.78**	0.14	**0.39**	0.12	**0.22**	0.08

TSWG: 1st census/2005	**0.00**	0.00	**0.78**	0.20	**0.47**	0.20	**0.78**	0.21	**1.69**	0.24	**1.83**	0.32	**1.25**	0.20	**4.56**	0.47
TSWG: 2nd census/2005	**0.00**	0.00	**1.10**	0.20	**2.18**	0.40	**1.09**	0.20	**2.00**	0.31	**5.72**	0.58	**1.81**	0.28	**4.72**	0.49
TSWG: 1st census/2006	**0.03**	0.03	**0.01**	0.01	**1.65**	1.50	**0.14**	0.11	**0.04**	0.02	**0.13**	0.07	**0.44**	0.12	**0.13**	0.04
TSWG: 2nd census/2006	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.44**	0.11	**0.65**	0.12	**0.35**	0.14	**0.06**	0.02
SRWG: 1st census/2005	**0.00**	0.00	**1.39**	0.20	**1.39**	0.31	**1.39**	0.20	**4.21**	0.51	**5.13**	0.53	**1.69**	0.24	**7.42**	0.64
SRWG: 2nd census/2005	**0.00**	0.00	**0.94**	0.17	**4.58**	0.54	**0.94**	0.17	**3.79**	0.44	**6.96**	0.60	**3.01**	0.36	**8.88**	0.80
SRWG: 1st census/2006	**0.04**	0.03	**0.31**	0.11	**0.15**	0.08	**0.13**	0.09	**0.36**	0.12	**1.04**	0.24	**0.92**	0.28	**0.42**	0.26
SRWG: 2nd census/2006	**0.01**	0.01	**0.43**	0.11	**0.25**	0.10	**0.01**	0.01	**0.82**	0.15	**1.43**	0.23	**0.43**	0.13	**0.17**	0.10
BWR: 1st census/2005	**0.00**	0.00	**0.07**	0.03	**0.18**	0.07	**0.07**	0.03	**0.63**	0.18	**0.86**	0.26	**1.26**	0.27		
BWR: 2nd census/2005	**0.00**	0.00	**0.17**	0.06	**0.36**	0.10	**0.17**	0.06	**0.81**	0.16	**3.29**	0.39	**1.13**	0.21		
BWR: 1st census/2006	**0.00**	0.00	**0.00**	0..00	**0.01**	0.01	**0.00**	0.00	**0.14**	0.01	**0.00**	0.00	**0.61**	0.25		
BWR: 2nd census/2006	**0.00**	0.00	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00	**0.13**	0.06	**0.04**	0.02	**0.11**	0.06		
BG: 1st census/2005	**0.00**	0.00	**0.41**	0.11	**1.00**	0.33	**0.42**	0.11	**1.97**	0.29	**1.65**	0.24	**2.26**	0.26	**4.94**	0.46
BG: 2nd census/2005	**0.06**	0.04	**0.83**	0.21	**1.01**	0.13	**0.83**	0.21	**1.40**	0.24	**2.75**	0.36	**1.69**	0.19	**2.55**	0.34
BG: 1st census/2006	**0.03**	0.02	**1.03**	0.33	**0.59**	0.12	**0.65**	0.11	**0.83**	0.14	**1.06**	0.18	**2.35**	0.55	**3.11**	0.52
BG: 2nd census/2006	**0.06**	0.03	**0.10**	0.05	**0.06**	0.02	**0.11**	0.06	**0.85**	0.12	**0.85**	0.16	**0.52**	0.17	**0.78**	0.26
BBWG: 1st census/2005	**0.01**	0.01	**1.10**	0.13	**0.19**	0.05	**1.10**	0.13	**2.63**	0.24	**4.09**	0.38	**1.78**	0.20	**5.32**	0.38
BBWG: 2nd census/2005	**0.07**	0.07	**1.16**	0.15	**2.42**	0.24	**1.16**	0.15	**2.74**	0.28	**5.85**	0.41	**2.16**	0.21	**5.72**	0.40
BBWG: 1st census/2006	**0.03**	0.02	**0.08**	0.05	**0.08**	0.02	**0.05**	0.02	**0.54**	0.13	**0.58**	0.12	**0.91**	0.23	**0.13**	0.03
BBWG: 2nd census/2006	**0.06**	0.03	**0.24**	0.06	**0.06**	0.02	**0.00**	0.00	**0.96**	0.15	**1.27**	0.16	**0.26**	0.07	**0.11**	0.03
GM: 1st census/2005	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**2.08**	0.80	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00
GM: 2nd census/2005	**0.00**	0.00	**0.00**	0.00	**0.08**	0.05	**0.00**	0.00	**0.03**	0.03	**0.00**	0.00	**0.17**	0.07	**0.28**	0.18
GM: 1st census/2006	**0.00**	0.00	**0.00**	0.00	**0.19**	0.10	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00
GM: 2nd census/2006	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00	**0.03**	0.03	**0.00**	0.00	**0.00**	0.00

Table 5.4. ANOVA and mean comparison results for density measurements of plants seeded in 2003.

SEEDED 2003/2004 DATA: FIRST CENSUS

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Treatment	**	1,4	+	1,4	ns	1,4	ns	1,4	ns	1,4	ns	1,4	ns	1,4	ns	1,4
Entry	ns	3,12	+	24,96	**	24,91	**	24,96	**	24,96	**	24,95	**	24,96	**	24,96
Treatment X Entry	ns	3,12	*	24,96	ns	24,91	ns	24,96	ns	24,96	ns	24,95	ns	24,96	ns	24,96

MAIN EFFECT LSMEANS (PLANTS PER SECTION)

	ID/CCK	ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Herbicide	0.1	0.05		0.01		0.01		0.03		0.54		0.42		0.5	
No Herbicide	1.07	0		0.01		0.01		0.03		0.57		0.67		0.45	
Yarrow															
Eagle	0.00	0.00	a	0.00	a	0.00	a	0.00	a	0.00	a	0.01	a		
Great Northern	0.00	0.00	a	0.00	a	0.00	a	0.00	a	0.00	a	0.00	a		
Crested WG															
Vavilov	0.00	0.01	a	0.00	a	0.00	a	0.01	a	0.18	b	1.15	a	0.64	a
CD II	0.00	0.05	a	0.00	a	0.01	a	0.07	a	3.28	a	1.21	a	1.37	a
Squirreltail	0.00														
Shaniko Plateau	0.00	0.02	a	0.00	a	0.01	a	0.00	a	1.87	a	1.48	a	1.00	a
Sand Hollow	0.00	0.01	a	0.01	a	0.00	a	0.00	a	0.25	b	0.23	b	0.12	b
Thickspike WG															
Bannock	0.00	0.01	a	0.00	a	0.00	a	0.02	a	0.40	b	0.73	a	0.26	b
Critana	0.00	0.04	a	0.00	a	0.00	a	0.05	a	2.07	a	1.14	a	1.61	a
Snake River WG															
SRDP	0.00	0.03	a	0.00	a	0.01	a	0.07	a	3.47	a	1.18	a	2.90	a
Secar	0.00	0.04	a	0.00	a	0.00	a	0.07	a	1.52	a	2.01	a	0.45	b
Basin WR															
Trailhead	0.00	0.03	a	0.00	a	0.00	a	0.05	a	3.02	a	0.18	a		
Magnar	0.00	0.02	a	0.00	a	0.00	a	0.02	a	0.41	b	0.29	a		
Bluegrass															
Hanford	0.00	0.00	a	0.00	a	0.00	a	0.00	a	0.06	b	0.52	a	0.26	a
Mountain Home	0.00	0.02	a	0.00	a	0.00	a	0.00	a	0.62	a	0.95	a	0.53	a

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
High Plains	0.00		0.01	a	0.00	a	0.00	a	0.01	a	1.04	a	0.64	a	0.66	a
Sherman	0.00		0.01	a	0.00	a	0.00	a	0.01	a	0.41	a	0.47	a	0.85	a
Bluebunch WG																
Anatone	0.00		0.05	a	0.00	a	0.00	a	0.37	a	2.09	a	0.74	ab	0.95	a
P-12	0.00		0.03	ab	0.00	a	0.00	a	0.11	ab	1.75	a	2.03	a	2.17	a
P-7	0.00		0.01	ab	0.01	a	0.00	a	0.04	b	0.93	ab	1.22	a	1.15	ab
Goldar	0.00		0.01	b	0.00	a	0.00	a	0.02	b	0.29	b	0.16	b	0.39	b
Cereals																
mountain rye	0.07	a	0.04	a	0.28	b	0.52	a	0.61	a	5.56	a	1.96	a	7.27	a
Stani rye	0.18	a	0.02	a	1.83	a	0.38	a	0.06	bc	1.32	b	0.89	ab	0.94	b
Regreen wheat X	0.19	a	0.01	a	1.05	a	0.35	a	0.04	c	0.88	b	0.43	ab	2.75	ab
Pioneer wheat X	0.14	a	0.02	a	0.47	b	0.25	a	0.18	b	1.40	b	0.34	b	3.10	ab
globemallow	0.00		0.00		0.00		0.00		0.00		0.00		0.01		0.00	
winterfat															0.00	
shadscale															0.27	
fourwing saltbush															0.04	
Rimrock IRG															0.00	
>CD II?	mt. rye Stani Regreen Pioneer		none		mt. rye Stani Regreen Pioneer		mt. rye Stani Regreen Pioneer		mt. rye Anatone		none		none		mt. rye	

SEEDED 2003/2004 DATA: SECOND CENSUS

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Treatment	**	1,4	*	1,4	*	1,4	+	1,4	ns	1,4	ns	1,4	+	1,4	*	1,4
Entry	ns	3,12	**	24,95	**	24,96	**	24,96	**	24,96	**	24,96	**	24,96	**	24,96
Treatment X Entry	ns	2,12	**	24,95	*	24,96	*	24,96	ns	24,96	ns	24,96	ns	24,96	**	24,96

MAIN EFFECT LSMEANS (PLANTS PER SECTION)

	ID/CCK	ID/CCB	OR/LB	OR/SC	UT/VH	UT/SS	NV/EV	NV/IR
Herbicide	0.02	0.03	0.03	0.03	0.01	0.46	0.00	0.17
No Herbicide	1.11	0.00	0.01	0.01	0.02	0.52	0.00	0.03

Yarrow								
Eagle	0.00	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	
Great Northern	0.00	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	
Crested WG								
Vavilov	0.00	0.01 a	0.00 a	0.01 b	0.00 a	0.16 b	0.00 a	0.03 a
CD II	0.00	0.02 a	0.00 a	0.14 a	0.02 a	1.43 a	0.00 a	0.10 a
Squirreltail	0.00							
Shaniko Plateau	0.00	0.01 a	0.01 a	0.03 a	0.01 a	1.21 a	0.00 a	0.11 a
Sand Hollow	0.00	0.01 a	0.02 a	0.01 a	0.00 a	0.12 b	0.00 a	0.07 a
Thickspike WG								
Bannock	0.00	0.01 b	0.00 a	0.00 a	0.01 a	0.63 a	0.00 a	0.04 a
Critana	0.00	0.07 a	0.00 a	0.02 a	0.02 a	1.55 a	0.02 a	0.11 a
Snake River WG								
SRDP	0.00	0.03 a	0.02 a	0.04 a	0.04 a	2.71 a	0.01 a	0.22 a
Secar	0.00	0.03 a	0.01 a	0.02 a	0.02 a	1.76 a	0.00 a	0.09 a
Basin WR								
Trailhead	0.00	0.03 a	0.00 a	0.00 a	0.01 a	1.31 a	0.00 a	
Magnar	0.00	0.00 a	0.01 a	0.00 a	0.00 a	0.91 a	0.00 a	
Bluegrass								
Hanford	0.00	0.00 a	0.00 a	0.00 a	0.00 a	0.05 b	0.00 a	0.00 a
Mountain Home	0.00	0.00 a	0.00 a	0.00 a	0.00 a	0.46 a	0.00 a	0.00 a
High Plains	0.00	0.00 a	0.00 a	0.00 a	0.01 a	0.46 a	0.00 a	0.00 a
Sherman	0.00	0.01 a	0.00 a	0.00 a	0.01 a	0.89 a	0.00 a	0.01 a
Bluebunch WG								
Anatone	0.00	0.02 a	0.04 a	0.01 ab	0.06 a	2.02 a	0.00 a	0.38 a
P-12	0.00	0.03 a	0.04 a	0.01 ab	0.05 a	1.48 a	0.00 a	0.18 a
P-7	0.00	0.02 a	0.03 a	0.02 a	0.02 ab	0.96 a	0.00 a	0.13 a
Goldar	0.00	0.00 a	0.00 b	0.01 b	0.01 b	0.14 b	0.00 a	0.02 b
Cereals								
mountain rye	0.22 a	0.06 a	0.96 ab	0.22 a	1.03 a	4.62 a	0.02 a	4.50 a
Stani rye	0.18 a	0.01 b	1.63 a	0.39 b	0.02 b	1.57 ab	0.19 a	0.81 b
Regreen wheat X	0.20 a	0.01 b	1.09 ab	0.42 b	0.04 b	0.84 b	0.01 a	1.45 ab
Pioneer wheat X	0.14 a	0.03 ab	0.55 b	0.25 b	0.05 b	1.74 ab	0.00 a	0.95 b
globemallow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

	ID/CCK	ID/CCB	OR/LB	OR/SC	UT/VH	UT/SS	NV/EV	NV/IR
winterfat								0.00
shadscale								0.12
fourwing saltbush								0.00
Rimrock IRG								0.01
>CD II?	mt. rye Stani Regreen Pioneer	none	mt. rye Stani Regreen Pioneer P-12 Anatone P-7	mt. rye Regreen	mt. rye	none	Stani Critana mt. rye	mt. rye Regreen Stani Pioneer Anatone

SEEDED 2003/2004 DATA: THIRD CENSUS

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Treatment	**	1,4	**	1,4	*	1,4	+	1,4	ns	1,4	ns	1,4	*	1,4	**	1,4
Entry	ns	3,12	**	24,96	**	24,96	**	24,96	**	24,95	**	24,96	**	24,91	**	24,95
Treatment X Entry	ns	3,12	**	24,96	**	24,96	*	24,96	**	24,95	ns	24,96	ns	24,91	**	24,95

MAIN EFFECT LSMEANS (PLANTS PER SECTION)

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Herbicide	1.30		0.03		0.09		0.03		0.01		0.23		0.00		0.20	
No Herbicide	0.04		0.00		0.03		0.01		0.00		0.27		0.00		0.03	
Yarrow																
Eagle	0.00		0.00	a	0.00	a	0.00	a	0.00	a	0.00	a	0.00	a		
Great Northern	0.00		0.00	a	0.00	a	0.00	a	0.00	a	0.00	a	0.00	a		
Crested WG																
Vavilov	0.00		0.01	a	0.02	a	0.02	b	0.00	b	0.17	b	0.00	a	0.07	a
CD II	0.00		0.02	a	0.06	a	0.10	a	0.01	a	0.44	a	0.02	a	0.15	a
Squirreltail	0.00															
Shaniko Plateau	0.00		0.01	a	0.12	a	0.02	a	0.00	a	0.41	a	0.00	a	0.11	a
Sand Hollow	0.00		0.01	a	0.03	b	0.00	a	0.00	a	0.09	b	0.00	a	0.06	a
Thickspike WG																
Bannock	0.00		0.02	a	0.00	b	0.00	a	0.00	a	0.28	b	0.00	a	0.08	a

Critana	0.00		0.06	a	0.05	a	0.01	a	0.00	a	1.35	a	0.68	a	0.11	a
Snake River WG																
SRDP	0.00		0.04	a	0.10	a	0.05	a	0.00	a	2.33	a	0.02	a	0.21	a
Secar	0.00		0.02	a	0.07	a	0.02	a	0.00	a	0.85	a	0.00	a	0.09	a
Basin WR																
Trailhead	0.00		0.02	a	0.07	a	0.00	a	0.00	a	0.38	a	0.00	a		
Magnar	0.00		0.00	a	0.05	a	0.00	a	0.00	a	0.16	a	0.00	a		
Bluegrass																
Hanford	0.00		0.00	b	0.00	a	0.00	a	0.00	a	0.00	b	0.00	a	0.00	a
Mountain Home	0.00		0.00	b	0.00	a	0.00	a	0.00	a	0.01	b	0.00	a	0.00	a
High Plains	0.00		0.00	ab	0.00	a	0.00	a	0.00	a	0.01	b	0.00	a	0.00	a
Sherman	0.00		0.02	a	0.01	a	0.00	a	0.00	a	0.38	a	0.00	a	0.01	a
Bluebunch WG																
Anatone	0.00		0.04	a	0.08	b	0.02	a	0.04	a	0.51	a	0.03	a	0.25	a
P-12	0.00		0.02	a	0.36	a	0.01	a	0.00	b	0.36	a	0.03	a	0.24	a
P-7	0.00		0.01	ab	0.13	ab	0.02	a	0.00	b	0.86	a	0.01	a	0.19	a
Goldar	0.00		0.00	b	0.01	c	0.00	a	0.00	b	0.15	b	0.00	b	0.02	b
Cereals																
mountain rye	0.58	a	0.11	a	0.93	a	1.05	a	0.14	a	2.41	a	0.43	a	2.65	a
Stani rye	0.19	ab	0.01	b	0.21	a	0.43	ab	0.01	c	1.22	ab	0.00	a	0.69	b
Regreen wheat X	0.18	ab	0.01	b	0.59	a	0.38	ab	0.02	b	0.66	b	0.00	a	1.47	ab
Pioneer wheat X	0.14	b	0.03	b	0.56	a	0.23	b	0.01	bc	1.39	ab	0.00	a	0.77	b
globemallow	0.00		0.01		0.00		0.00		0.00		0.00		0.00		0.00	
winterfat															0.00	
shadscale															0.12	
fourwing saltbush															0.01	
Rimrock IRG															0.01	
>CD II?	mt. rye		mt. rye		mt. rye		mt. rye		mt. rye		none		none		mt. rye	
	Stani				Stani		Stani		Anatone						Regreen	
	Regreen				Regreen		Regreen								Pioneer	
	Pioneer				Pioneer										Stani	
					P-12											

Table 5.5. ANOVA and mean comparison results for density measurements of plants seeded in 2004.

SEEDED 2004/2005 DATA: FIRST CENSUS

	ID/CCK		**ID/CCB**		**OR/LB**		**OR/SC**		**UT/VH**		**UT/SS**		**NV/EV**		**NV/IR**	
Treatment	*	1,4	**	1,4	*	1,4	*	1,4	ns	1,4	*	1,4	ns	1,4	ns	1,4
Entry	**	3,12	**	21,79	**	21,74	**	21,84	**	21,83	**	21,84	**	21,79	**	19,76
Treatment X Entry	**	3,12	ns	21,79	**	21,74	ns	21,84	+	21,83	*	21,84	**	21,79	ns	19,76

MAIN EFFECT LSMEANS (PLANTS PER SECTION)

	ID/CCK	ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Herbicide	1.49	0.06		0.03		0.05		0.31		0.64		0.05		1.19	
No Herbicide	0.59	0.01		0.01		0.01		0.27		0.06		0.14		0.92	
Yarrow															
Eagle	0.00	0.00		0.00		0.00		0.00		0.00		0.00			
Great Northern	0.00	0.00		0.00		0.00		0.00		0.00		0.00			
Crested WG															
Vavilov	0.00	0.06	a	0.00	b	0.01	a	0.36	a	0.05	b	0.07	a	2.25	a
CD II	0.00	0.13	a	0.01	a	0.02	a	0.82	a	0.48	a	0.15	a	5.82	a
Squirreltail															
Shaniko Plateau	0.00	0.02	a	0.00	b	0.00	a	0.09	a	0.03	a	0.10	a	1.13	a
Sand Hollow	0.00	0.00	b	0.01	a	0.00	a	0.06	a	0.01	a	0.01	b	0.27	a
Thickspike WG															
Bannock	0.00	0.00	a	0.00	b	0.00	a	0.01	b	0.07	a	0.03	a	0.63	a
Critana	0.00	0.01	a	0.00	a	0.01	a	0.70	a	0.05	a	0.03	a	1.76	a
Snake River WG															
SRDP	0.00	0.13	a	0.02	a	0.01	a	1.32	a	0.69	a	0.52	a	2.48	a
Secar	0.00	0.06	a	0.00	b	0.01	a	1.21	a	1.10	a	0.02	b	3.98	a
Basin WR															
Trailhead	0.00	0.00	a	0.01	a	0.00	a	0.01	a	0.01	a	0.04	a		
Magnar	0.00	0.00	a	0.00	b	0.00	a	0.01	a	0.01	a	0.03	a		
Bluegrass															
Hanford	0.00	0.00	b	0.01	a	0.01	a	0.04	ab	0.01	bc	0.03	b	0.14	b
Mountain Home	0.00	0.01	a	0.00	a	0.02	a	0.12	ab	0.00	c	0.64	a	0.74	a

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
High Plains	0.00		0.00	ab	0.00	a	0.01	a	0.24	a	0.05	b	0.15	a	1.43	a
Sherman	0.00		0.00	ab	0.00	a	0.00	a	0.03	b	0.42	a	0.11	ab	1.74	a
Bluebunch WG																
Anatone	0.00		0.13	a	0.00	a	0.05	a	1.19	a	4.75	a	0.12	a	3.07	a
P-12	0.00		0.05	a	0.00	ab	0.02	ab	0.51	a	0.87	a	0.09	ab	2.91	a
P-7	0.00		0.04	a	0.00	ab	0.02	ab	0.75	a	0.28	b	0.06	ab	1.14	a
Goldar	0.00		0.00	b	0.00	b	0.00	b	0.04	b	0.09	b	0.02	b	0.81	a
Cereals																
mountain rye	0.10	c	1.87	a	3.10	bc	3.56	ab	10.73	a	8.39	a	0.48	a	4.42	a
Stani rye	0.91	b	0.26	b	1.87	c	0.99	b	3.35	a	3.90	a	0.09	b	0.14	b
Regreen wheat X	3.00	a	1.95	a	6.71	ab	2.87	ab	3.31	a	9.59	a	0.12	ab	0.10	b
Pioneer wheat X	2.89	a	3.08	a	9.22	a	8.57	a	9.38	a	12.94	a	0.69	a	0.40	b
globemallow	0.00		0.00		0.00		0.00		0.00		0.00		0.00			
winterfat																
shadscale																
fourwing saltbush																
Rimrock IRG																
>CD II?	mt. rye Stani Regreen Pioneer		Pioneer Regreen mt. rye		Pioneer Regreen mt. rye Stani		Pioneer Regreen mt. rye Stani		mt. rye Pioneer		Pioneer Regreen mt. rye Anatone Stani		none		none	

SEEDED 2004/2005 DATA: SECOND CENSUS

	ID/CCK		ID/CCB		OR/LB		OR/SC		UT/VH		UT/SS		NV/EV		NV/IR	
Treatment	ns	1,4	ns	1,4	+	1,4	ns	1,4	ns	1,4	ns	1,4	*	1,4	ns	1,4
Entry	**	3,12	**	21,83	**	21,74	**	21,82	**	21,84	**	21,79	**	21,84	**	19,76
Treatment X Entry	**	3,12	+	21,83	+	21,74	**	21,82	ns	21,84	**	21,79	ns	21,84	ns	19,76

MAIN EFFECT LSMEANS (PLANTS PER SECTION)

	ID/CCK	ID/CCB	OR/LB	OR/SC	UT/VH	UT/SS	NV/EV	NV/IR
Herbicide	1.28	0.07	0.30	0.72	0.24	1.56	0.12	0.94

No Herbicide	0.81		0.02		0.10		0.25		0.17		1.48		0.38		0.58	
Yarrow																
Eagle	0.00		0.00		0.00		0.00		0.00		0.00		0.00			
Great Northern	0.00		0.00		0.00		0.00		0.00		0.00		0.00			
Crested WG																
Vavilov	0.00		0.02	b	0.07	a	0.09	b	0.08	b	0.39	b	0.06	b	1.32	b
CD II	0.00		0.17	a	0.12	a	1.18	a	0.58	a	3.94	a	0.69	a	7.59	a
Squirreltail																
Shaniko Plateau	0.00		0.03	a	0.01	b	0.05	a	0.33	a	2.14	a	0.53	a	1.16	a
Sand Hollow	0.00		0.00	b	0.06	a	0.13	a	0.20	a	0.62	b	0.12	a	0.38	a
Thickspike WG																
Bannock	0.00		0.00	b	0.01	b	0.12	b	0.01	b	1.32	a	0.03	b	0.57	a
Critana	0.00		0.20	a	1.00	a	1.10	a	0.69	a	3.37	a	0.68	a	1.94	a
Snake River WG																
SRDP	0.00		0.01	b	3.57	a	1.54	a	1.73	a	2.60	a	2.30	a	3.50	a
Secar	0.00		0.13	a	1.29	a	0.79	a	0.25	b	3.91	a	0.11	b	4.66	a
Basin WR																
Trailhead	0.00		0.00	a	0.00	a	0.06	a	0.03	a	2.27	a	0.03	a		
Magnar	0.00		0.00	a	0.00	a	0.02	a	0.01	a	1.43	a	0.04	a		
Bluegrass																
Hanford	0.00		0.00	b	0.01	c	0.01	b	0.00	c	0.00	b	0.01	b	0.00	c
Mountain Home	0.00		0.02	a	0.03	b	0.17	a	0.02	b	0.01	b	0.07	ab	0.03	b
High Plains	0.00		0.04	a	0.04	b	0.79	a	0.18	a	0.99	a	0.35	a	0.22	b
Sherman	0.00		0.01	ab	0.29	a	0.28	a	0.14	a	2.57	a	0.44	a	1.43	a
Bluebunch WG																
Anatone	0.00		0.03	a	0.84	a	1.53	a	1.03	a	8.35	a	0.29	a	5.27	a
P-12	0.00		0.09	a	0.82	a	0.57	a	0.34	a	4.10	ab	0.21	ab	2.64	a
P-7	0.00		0.02	a	0.23	a	1.42	a	0.19	ab	2.51	b	0.35	a	1.54	ab
Goldar	0.00		0.02	a	0.04	b	0.06	b	0.03	b	0.56	c	0.04	b	0.43	b
Cereals																
mountain rye	0.25	c	4.35	a	6.06	a	9.15	a	8.36	a	9.16	a	4.24	a	8.15	a
Stani rye	0.89	b	0.39	b	3.16	a	4.97	a	1.25	b	4.47	a	0.40	b	0.22	b
Regreen wheat X	2.45	a	1.35	ab	6.76	a	4.59	a	1.02	b	8.77	a	0.87	ab	0.16	b
Pioneer wheat X	1.96	a	4.02	a	7.45	a	7.25	a	5.10	ab	12.99	a	0.79	ab	0.55	b

globemallow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
winterfat								
shadscale								
fourwing saltbush								
Rimrock IRG								
>CD II?	mt. rye Stani Regreen Pioneer	mt. rye Pioneer Regreen	Pioneer Regreen mt. rye Stani SRDP Secar Critana Anatone P-12	mt. rye Pioneer	mt. rye Pioneer	Pioneer	none	none

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Chapter 6 – Experiment 2: Plant functional groups and Soil N: Cheatgrass and native plant responses

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INTRODUCTION

Two biological features contribute to the remarkable success of cheatgrass (Smith *et al*. 1997): prolific seed production and high competitive ability. Seed production by cheatgrass can be 10-100 times greater on burned sites in the first year after fire, and although population density may be relatively small during this first year after a fire, field and modeling studies demonstrate that cheatgrass populations have an 80-90% risk of exploding to densities near 10,000 plants m^{-2} within 10 years (Young & Evans 1978; Pyke 1995). In addition, cheatgrass is a strong competitor (displacing root systems – Melgoza and Nowak 1991) and breaks dormancy earlier in the season than most native species (with greater root elongation at low soil temperatures - Harris 1967) thus it competes effectively with native species for soil water, negatively affecting the water status and productivity of established perennial plants (Melgoza *et al.* 1990).

In order to shift the balance between cheatgrass and native species in areas that have become cheatgrass-dominated, it is necessary to understand and utilize the processes affecting species interactions in this system. Restoring cheatgrass-invaded rangeland will require that cheatgrass seed output is reduced and that cheatgrass competitive edge is diminished. To that end our second experiment investigates the effects of species functional groups and soil nitrogen availability on cheatgrass success and native species establishment. Cheatgrass grows well in high nitrogen conditions and is sensitive to nitrogen fertility, while most native species are tolerant of low nitrogen conditions. Based on this knowledge, we hypothesize that by reducing soil nitrogen availability we can tip the balance of competition in favor of the native species, promoting establishment.

Soil nitrogen availability can be dramatically reduced by addition of carbon to soils, and carbon amendment is a commonly used restoration technique in some invaded ecosystems (Haubensak et al in prep). The carbon input stimulates production of microbial biomass, which in turn takes up available soil nitrogen and sequesters it. Thus addition of carbon to soils decreases the amount of nitrogen available for plant use. If carbon is applied at a critical time (for instance, just prior to root elongation of cheatgrass), it might be possible to reduce cheatgrass growth and promote native species establishment. However, adding large amounts of labile carbon to large areas of the Great Basin is not a viable management option. Therefore we also chose to test the effectiveness of establishing a functionally diverse suite of six native species. By selecting a range of functional types (grasses and forbs, early season and late season, deep rooted and shallow rooted), we attempted to reduce open niche space for cheatgrass to take advantage of. We hypothesize that the range of native species growth forms and seasonalities will allow maximum use of the available resource spectrum in space and time, giving the best possible chance to pre-empt resources from cheatgrass and thus reduce its competitive dominance. We compared the performance of this six-species mix to that of each species in monoculture. Finally we chose to compare the performance of native species and a native mix to that of a commonly planted Siberian wheatgrass cultivar (*Agropyron fragile* 'Vavilov'). The carbon addition, cheatgrass addition or removal, and planted species treatments were applied in a split-plot design at each of our eight study areas, and iterations of the experiment were established in 2003 and 2004. Details of the experimental design are given in the 'Methods' section of this chapter, and the remainder of this chapter will deal with this "core" experiment. Two additional aspects of competitive interactions were investigated at a subset of study areas. These experiments are described briefly below, but will be dealt with in detail in the subsequent chapters of this report.

The questions we sought to answer with this experiment are:

1 Did sucrose reduce soil N?
2 Did the 'target species' benefit?
    a. Did sucrose facilitate establishment?
    b. Did cheatgrass reduce native recruitment?
3 Was cheatgrass adversely affected?
    a. Did the 6-species mix reduce cheatgrass?
    b. Was cheatgrass seed output, biomass, or density reduced?

Experiment 2 Density Effects

Seed limitation and seeding efficiency are of paramount importance in restoration projects. In many cheatgrass-dominated landscapes there are few or no native bunchgrasses remaining to form seed sources for re-colonization, so areas must be re-seeded. However, native seed is expensive, so a balance must be struck between increasing probability of native establishment by increasing seeding rate and ensuring that management actions are not prohibitively expensive. Additionally, the density of cheatgrass in a given location is likely to affect the establishment success of planted perennial seedlings. To investigate the relationships between seeding rate, competitive interactions, and cheatgrass density we established additional experimental plots at the Nevada High Precipitation site (Eden Valley NV). In these plots we manipulated seeding rate of cheatgrass, native species mix, and Siberian wheatgrass. Details of this experiment are given in Chapter 7 of this report.

Experiment 2 Secondary Weeds

Following invasion of cheatgrass and alteration of the fire cycle in sagebrush ecosystems, other weed species ('secondary weeds') frequently establish and can become problematic invaders in their own right. Medusahead (*Taenatherium caput-medusae*), squarrose knapweed (*Centaurea virgata*), and rush skeletonweed (*Chondrilla juncea*) are three species of concern. At four sites (Utah low precipitation, Oregon high precipitation, and both sites in Idaho), we established additional experimental plots to investigate the interactions between cheatgrass, the native species mix, Siberian wheatgrass, and one of the three secondary weed species listed above. Details of this experiment are given in Chapter 8 of this report.

METHODS

Experimental Design

The study was established as a randomized split-plot at each of eight sites (**Fig. 6.1**). For all portions of Experiment 2, there were two levels of carbon addition (none or 150g C m^{-2}) applied as the whole-plot factor, with three replicates. For the 'core' experiment, repeated at each of the eight sites, the split-plot factors were presence of cheatgrass (cheatgrass weeded out or 300 PLS m^{-2} added) and the identity of the 'target' perennial species (native monoculture, 6 species mix, Siberian wheatgrass, or unseeded control).

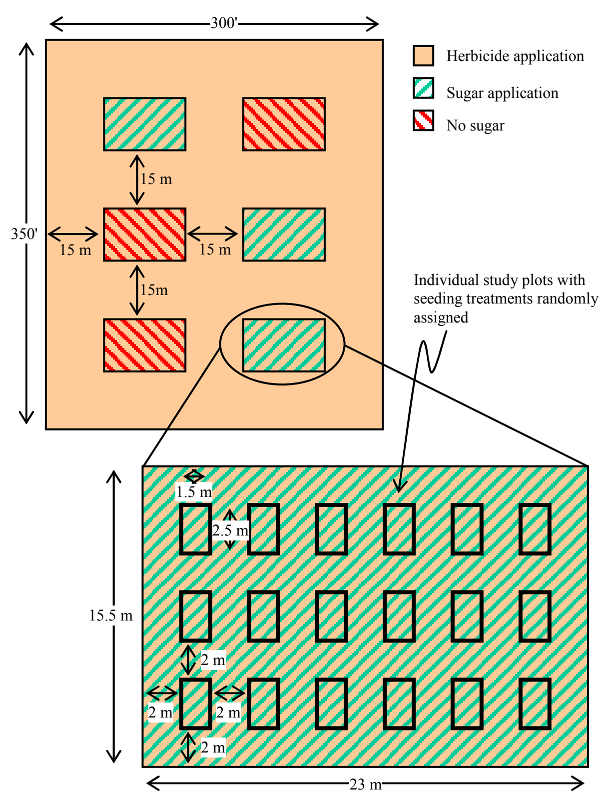

Fig. 6.1. Plot configuration for one planting year of the core portion of Experiment 2, showing layout of 6 plots in a randomized design at top and details of one plot with 18 subplots below.

We chose the following native species because they encompassed a range of growth forms and phenologies (see **Table 6.1**):

Table 6.1: species used in Experiment 2 native mix.

Species	Common Name	Life form	Phenology and water use	Rooting morphology
Achillea millefolium	Western Yarrow	Forb	late	rhizomatous root mat
Artemisia tridentata	Wyoming big sagebrush	Shrub	Year round	Spreading, uses entire soil profile
Elymus multisetus	Squirreltail	Bunchgrass	Early to mid	Shallow to mid, fibrous
Poa secunda	Sandberg's bluegrass	Bunchgrass	Early	Shallow root mat
Pseudoroegneria spicata	Bluebunch wheatgrass	Bunchgrass	Mid to late	Extensive, fibrous
Sphaeralcea coccinea	Scarlet globemallow	Perennial forb	Early, drought tolerant	

In the spring prior to seeding, a large area was sprayed with herbicide to remove existing cheatgrass and other weeds, then the 1.5 m by 2.5 m experimental plots and sub-plots were marked using PVC pipes, according to the diagram in **Fig. 6.1**. Corners of permanent monitoring quadrats were marked with nails and metal washers. All vegetation and litter was cleared from plots prior to seeding, and trash was removed from the study site. Sugar treatments were randomly assigned to whole plots, and seeding treatments were randomly assigned to sub-plots. At the time of seeding, we used rakes to gently scarify the soil to a depth of approximately 1 cm, and then we broadcast a mix of seed and rice hulls (the rice hulls made it easier to seed and ensured even distribution of seed across the plot). At the same time, we broadcast granulated cane sugar at a rate of 100g C m^{-2}. Plots were gently raked again to incorporate seed and sugar into the soil, then packed with a roller-packer, sprayed with a fine mist of water to prevent seed from blowing, and covered with jute mesh which was pinned down using landscape staples. Seeding took place in late October and early November. The same experimental set-up was repeated in 2003 and 2004 in adjacent locations.

In March of the year following seeding, we broadcast an additional dose of granulated cane sugar equaling 50g C m^{-2}. This was left on the soil surface rather than raked in to prevent uprooting tiny seedlings. We weeded any non-target plants (that is, any plants that were not species included in the seed treatment for that sub-plot) from the sub-plots in March, May, and June in the first year of growth. We did not weed in subsequent years.

Sampling

Sampling for this experiment evolved with each sampling season as we refined the techniques and determined what data would be most informative and time-efficient to collect. Details of the sampling are described below.

2004 season density, survival and biomass

In 2004, we attempted to track emergence and survival of cheatgrass and native species in the plots seeded with a 6-species mix by marking all individuals within permanent quadrats (1 m^2 for native species, 0.5 m^2 for secondary weeds, and 0.1 m^2 for cheatgrass) at three times during the first growing season. We used wire loops of different colors to mark different species and indicated individuals first found on different sampling dates by adding beads to the wire loops (thereby tracking emergence). Additionally, we did 'intensive surveys' (counts of individuals per unit area) at 4 times during the growing season for control plots and plots seeded with Vavilov. All other plots were counted only in June 2004. At each of the four sampling times in 2004, we measured soil water content at each plot using hand-held TDR probes.

At the end of the growing season (when cheatgrass seed had set but not dropped; late June), we conducted censuses of each plot, counting number of target perennial species in a 1 m^2 quadrat and counting cheatgrass individuals in a 0.1 m^2 quadrat. We then selected up to 15 cheatgrass plants from each plot that had cheatgrass and measured basal diameter and height for each individual. These plants were then collected, separated into seed and foliar biomass, viable seeds were counted and weighed, and foliage was dried at 60°C then weighed. Additionally, if any target species produced seed, these were collected, counted, and weighed (no target species biomass was collected). After processing, all seeds were returned to the plots so that population dynamics could be tracked through time. In Idaho and Oregon sites, only plots without cheatgrass were sampled in June (except for those plots undergoing the survival or intensive monitoring censuses).

2005 season density and biomass

Because the intensive monitoring of tagged individuals proved to be extremely time consuming, we did not track survival in 2005. Instead, we sampled density of target species and cheatgrass early in the growing season (mid-late May in most sites) and at the end of the growing season (mid-late June in most sites) for both the 2003-seeded and 2004-seeded plots. We also conducted a census of target individuals in March 2005 in 2003-seeded plots to assess winter green-up and overwinter survival. As in 2004, we collected up to 15 cheatgrass individuals per plot at the end of the growing season and collected inflorescences of target species when they occurred, then processed them as above. We did not measure diameter and height of cheatgrass or target species in 2005.

2006 season density, biomass, and plant size

In 2006, we sampled density of target species and cheatgrass in May and June for plots seeded in 2004, and sampled in June only for plots seeded in 2003. We collected up to 15 cheatgrass plants per plot and processed them as in 2004 and 2005 to assess vegetative biomass, seed biomass and seed output. For target species we again collected inflorescences and measured seed as in 2004 and 2005. To assess size of target perennial plants without harvesting them, we measured plants using calipers and counted tillers and inflorescences when appropriate. For grasses, we measured basal diameter, longest extended leaf length, number of tillers, number of inflorescences, and height of tallest inflorescence. For sagebrush, we measured height, canopy diameter at the widest point, and diameter perpendicular to the first diameter measurement. For forbs, we measured the basal rosette at its widest diameter and perpendicular diameter, and we counted inflorescences and measured the height of the tallest inflorescence.

Soil moisture content

At each sampling period, we measured soil moisture using hand-held time-domain reflectometry (TDR) probes that extended 20 cm into the soil. We made two measurements per experimental plot, and then averaged these. In the first season, we found that data from Oregon and Idaho sites were highly variable and suspect (greater than 100% moisture readings in some cases). This was likely due to the rocky saline soils at the sites. In subsequent years, we ceased collecting TDR moisture data in Oregon and Idaho, but at Utah and Nevada sites we continued to sample soil moisture every time we sampled density. In Nevada, we also established an automated TDR system with probes installed in a subset of experimental plots in the 2003 seeding. These probes were connected to a data logger and logged soil moisture information daily.

Seedbank

To evaluate the pre-existing seed bank, we sampled the Experiment 2 areas after the last herbicide application and before the fall seeding for both the 2003 and 2004 seedings of the experiment. At each site, we randomly selected 8 sub-plots per whole plot. At each randomly selected sub-plot, we placed a 0.1 m^2 quadrat to the right of the plot's marker post and at the mid-point of the sub-plot's longest edge (5 cm into the buffer zone between plots). We collected a 5cm diameter by 5cm depth core from each corner of the quadrat, divided the cores into 'litter/surface' and 'soil' segments, and bulked the samples to provide one composite sample per depth, per sub-plot. We mixed litter samples with 300g sterilized sand, and then moistened all samples to field capacity. We placed the samples in cold storage (1-2 ^{o}C) for 60 days, and then spread the samples over sterilized sand in trays in a greenhouse. We kept samples moist and monitored emergence every few days, counting and removing seedlings as they became identifiable. When no further emergence was observed, trays were allowed to dry for 30 days, and then were watered again and additional emergence assessed. Nomenclature follows the PLANTS database (USDA, NRCS 2006).

Data Analyses

Below, we summarize the datasets we accumulated through the course of this study and outline the analyses that have been or will be conducted. Additionally, these data will contribute to our 'Integrated Statistics Strategy' as we link the pieces of our data into a cohesive explanatory model (Chapter 9). In all cases, where mixed model ANOVA was used to test for differences among treatments, data were transformed as necessary to meet the assumptions of ANOVA. SAS 9.1 statistical software was used for analyses (SAS Institute © 2003, Cary NC).

Density counts

We used mixed model, repeated measures ANOVA to test for the effects of sugar treatment, time, cheatgrass presence, and seeded species on density of target seedlings. We also used mixed model, repeated measures ANOVA to test the effects of sugar treatment, time and seeded species on cheatgrass density. Data were either square-root or log-transformed as necessary to meet the assumptions of ANOVA. If analysis of the residuals revealed large outliers, these outliers were deleted from the dataset.

Because the replicated whole plots of the individual site study designs are subsamples when we move to analyzing all sites together (D. Turner, pers comm.), we calculated averages for each plot type across the three replicate sugar treatment plots at each site. This gave one value for each sugar treatment by seeding treatment combination, for each site, for each year. This substantially simplifies the hierarchical model and makes repeated measures analysis possible. In addition, it reduces the number of zero values in the data set, making the data more appropriate for ANOVA.

Because of the difficulty of conducting repeated measures ANOVA when sampling is at uneven intervals and because of missing cells in the sampling matrix (not all plots and sites were sampled at all dates), we averaged across the two sampling dates per year for 2005 and 2006 in order to conduct repeated measures analyses. There was only one sampling date in 2004 (June) when all plots were sampled. Because we did not have data from all 2003-seeded plots in OR and ID for 2004 and 2006, we analyzed only UT and NV sites in the repeated measures analyses for 2003 seedings. We used all sites in the repeated measures analysis of 2004 seedings. Because very few target individuals were ever counted in control plots or plots seeded with globemallow, these plots were dropped from the analysis of target species density. Models were initially run with precipitation as a fixed effect, but this was never a significant factor and because it added substantial complexity to the models and reduced statistical power, we dropped it from the final analyses.

Cheatgrass biomass and seed output

Cheatgrass biomass and seed output were analyzed using mixed model ANOVA, including all sites in each model. For the 2004 sampling season, seeds per plant and biomass per plant were analyzed; data could not be scaled to a per m^2 basis. For the 2005 sampling season, we analyzed weight and seeds per plant and per m^2, and we separated data from the 2003 and the 2004 seeding years. Thus, there were two variables and one data set analyzed for 2004 sampling, and 4 variables and two datasets analyzed for 2005 samplings. Samples collected in 2006 are still being processed, so no data were available from the 2006 sampling season.

Seedbank

The numbers of seedlings emerging from our soil seed bank samples were compiled into tabular and graphical summaries by site, year, species and functional groups.

Soil moisture data – TDR

Soil moisture data from Utah and Nevada sites (plots grouped by sugar and cheatgrass treatment) are presented in **Fig, 6.10** (data for 2006 have not been entered or processed yet). In addition to graphing changes in soil moisture through time, we conducted ANOVA to test for effects of cheatgrass and sucrose addition on soil moisture in May and June 2004 and 2005.

Data from the automated TDR system have not yet been processed for analysis. Once these data are available, we can compare automated VS hand-held results and track changes in soil moisture with time. Additionally, we intend to analyze soil moisture and cheatgrass density, seedset, and biomass data concurrently.

Survival of marked individuals (2004 sampling), plant size (2006 sampling), and target seed output, (2004-2006)

These datasets have not yet been compiled or analyzed. We will create survival curves for each cohort tracked in the 2004 sampling season, and if differences are apparent, we will conduct formal survival analyses. There were not enough plants producing seed for us to conduct a statistical analysis of target species seed production, but we will summarize the data as appropriate.

RESULTS

Density of Target Species

For the 2003 seedings in Utah and Nevada sites, we used a square-root transformation of the target species densities. There was a substantial effect of time on target species density ($F_{2,\ 168}$=100.23, p<0.0001) with the highest target densities present in 2004, and significantly fewer seedlings present in each subsequent year (**Fig 6.2**). There was no significant effect of sugar application, nor was there a significant sugar by time interaction. The identity of the planted species was significant ($F_{6,\ 168}$=4.27, p=0.005) and there was a significant time by species interaction ($F_{12,\ 168}$= 8.11, p<0.001). *Pseudoroegneria spicata* had the highest density, followed by mix plots, *Artemisia tridentata*, Vavilov, *Elymus multisetus*, *Achillea millefolium*, and finally *Poa secunda*. The species by time interaction is more difficult to interpret but is likely due in part to the pattern displayed by *Poa secunda*. *Poa* density was low in 2004, increased in the 2005 sampling, and declined from 2005 to 2006. All other species declined steadily through time, though some species (*e.g. Pseudoroegneria spicata*) declined more dramatically than others (also attributing to the interaction).

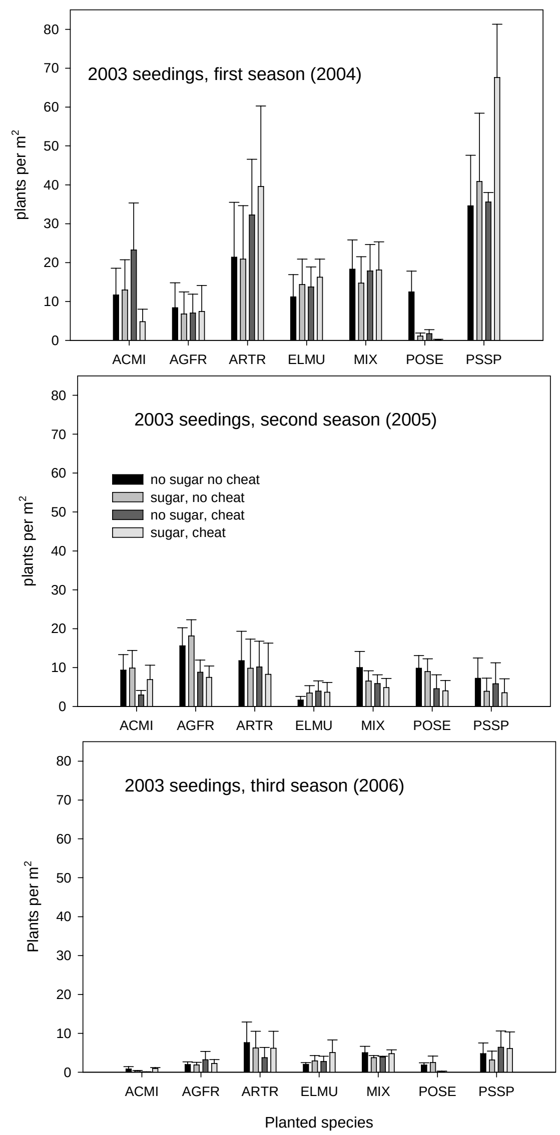

Fig. 6.2: Density of target species (+ SE) in 2003 seedings, sampled in each subsequent year. Data are from UT and NV sites only.

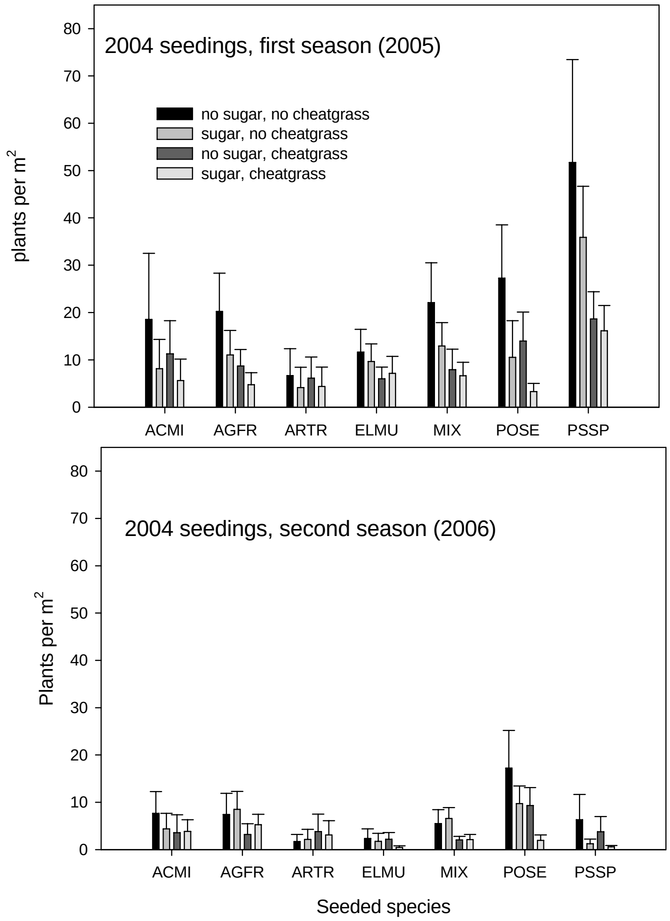

Fig. 6.3: Density of target species in 2004 seedings, (+ SE) sampled in each subsequent year.

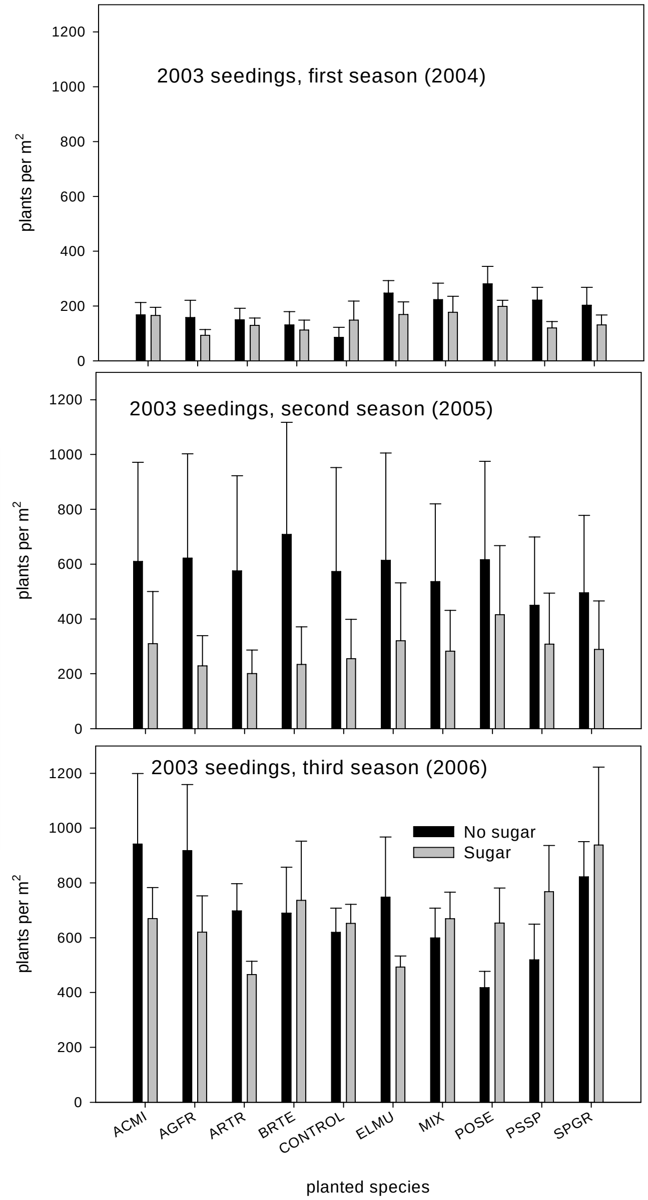

Fig. 6.4: Density of cheatgrass plants in 2003 seedings sampled in each subsequent year. Data from NV and UT sites only.

Fig. 6.3 shows the data for the 2004 seedings. We used a square-root transformation on these data as well. Year of sampling was the most significant influence ($F_{1,\ 196}$ = 106.9, p<0.0001) with more individuals counted in 2005 than in 2006. There was a marginally significant year by sugar treatment interaction ($F_{1,\ 196}$ = 397, p=0.048), in which the highest target density was found in 2005 in non-sugared plots, second highest in 2005 sugared plots, and by 2006 there was no difference between sugared and non-sugared plots (both were significantly lower than either type of plot in 2005). There were significantly higher densities of target individuals in plots without cheatgrass ($F_{1,112}$=26.82, p<0.0001). The planted species were significantly different in densities ($F_{6,\ 112}$=11.52, p<0.0001) and there was a significant time by species interaction ($F_{6,\ 112}$=11.9, p<0.0001). In this iteration of the experiment, *Pseudoroegneria spicata* was again the most abundant species, this time followed by *Poa secunda*, the mix, Vavilov, *Achillea millefolium*, *Elymus multesetus* and finally *Artemesia tridentata*. The significant interaction appears to be due to different rates of decline in the different species, with *Pseudoroegneria spicata* and *Elymus multesetus* showing dramatic declines from 2005 to 2006, and *Poa secunda* density not significantly changing through time.

Cheatgrass Density

Analyses were performed on log-transformed data for cheatgrass density, and results are presented in **Figs. 6.4 and 6.5**. For 2003 seedings, cheatgrass density increased with time ($F_{2,\ 120}$=274.1, p<0.0001), with less cheatgrass in 2004 than in 2005 or 2006 (which did not differ from each other). Sucrose addition resulted in significantly less cheatgrass ($F_{1,3}$= 13.85, p=0.034). There was a significant time by sucrose interaction, with the largest difference between sugar treatments showing up in 2005 ($F_{18,\ 120}$= 6.21, p=0.0027). There was also a significant time by planted species interaction (($F_{18,120}$=1.83, p=0.03), possibly because of a large increase in density with time occurring in control plots (which initially had the lowest density).

For the 2004 seedings, density in 2006 was higher than in 2005 (F+1, 264=1237.9, p<0.001) and there was a significant effect of sucrose with sugared plots having lower density than non-sugared plots ($F_{1,7}$=12.94, p=0.009). There was no treatment by time interaction, nor any other significant effects. Initially we ran the analysis including control plots (background cheatgrass) and in this model there was no overall effect of sugar, but there was a significant effect of planting treatment and a significant time by treatment interaction (sugar affected density in 2006 but not 2005). The significant species effect was simply due to higher densities where cheatgrass was planted (*ie.* controls were substantially lower than all other treatments) and several control plots had zero cheatgrass, so we removed the control plots from the analysis in order to get a better model fit.

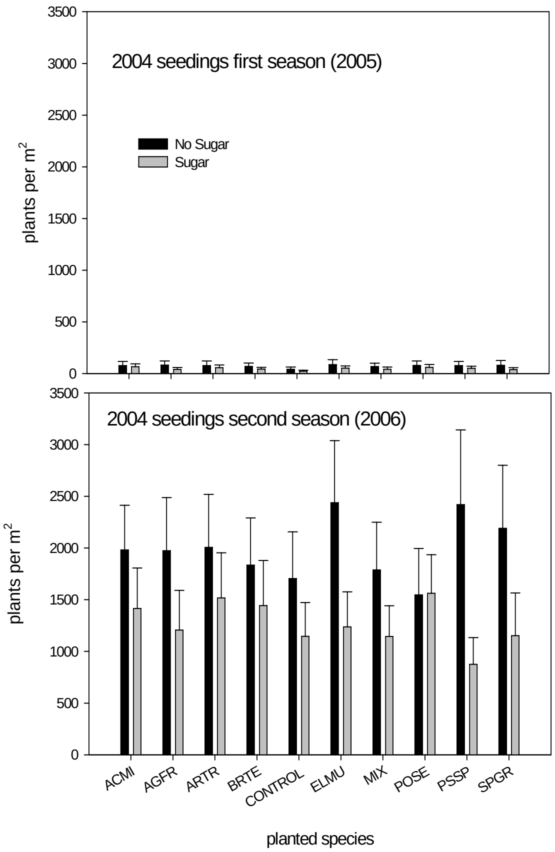

Fig. 6.5: Density of cheatgrass plants in 2004 seedings (+ SE) sampled in each subsequent year. Data are from all eight sites combined.

Cheatgrass Biomass and Seed Output

Data from the 2004 and 2005 sampling seasons were analyzed separately, but all sites were included in the same mixed-effects model (with site as a blocking factor). For the 2004 sampling, we only analyzed number of seeds and weight per plant in order to use data from all sites (cheatgrass density data were not collected from all plots in OR and ID sites in 2004). For 2005 sampling, we analyzed 2003 and 2004 seedings separately. Data were square-root transformed (for counts) or log-transformed (for weights) as appropriate to meet ANOVA assumptions.

In 2004, which was one season after seeding and application of sucrose, there was a significant difference between sugar and non-sugar plots with significantly larger plants ($F_{1,7}$=39.31, p=0.0004) and significantly more seeds ($F_{1,7}$ = 17.28, p=0.004) in areas where sugar was not applied (**Fig. 6.6**). There was a significant effect of target species on plant size ($F_{8,354}$= 3.1, p=0.002) such that cheatgrass plants growing with Vavilov or in control (unseeded) plots were the largest and cheatgrass plants growing with sagebrush were the smallest; however, the F value is small compared to the degrees of freedom.

In 2005, there were numerous plots where there was no cheatgrass collected and there were several plots with very few, very large plants, so we removed zeros and extreme values from the data set in order to meet the ANOVA assumptions. Again data were square-root or log transformed as appropriate (untransformed values are presented in **Fig. 6.6**). For 2003 seedings, both weight per cheatgrass plant and number of seeds produced per plant showed significant or marginally significant influences of sucrose application (weight: $F_{1,7}$=7.33, p=0.03; seeds: $F_{1,7}$=4.69, p=0.067). In the second season after sucrose application (*ie*. 2003 seedings measured in 2005) individual plants were slightly larger and produced more seeds in plots where sucrose had been previously added. Because sucrose resulted in lower cheatgrass density in the second season (see **Fig. 6.4** and other density results for details), there were no significant effects on biomass or seed production per m^2 (**Fig. 6.7**).

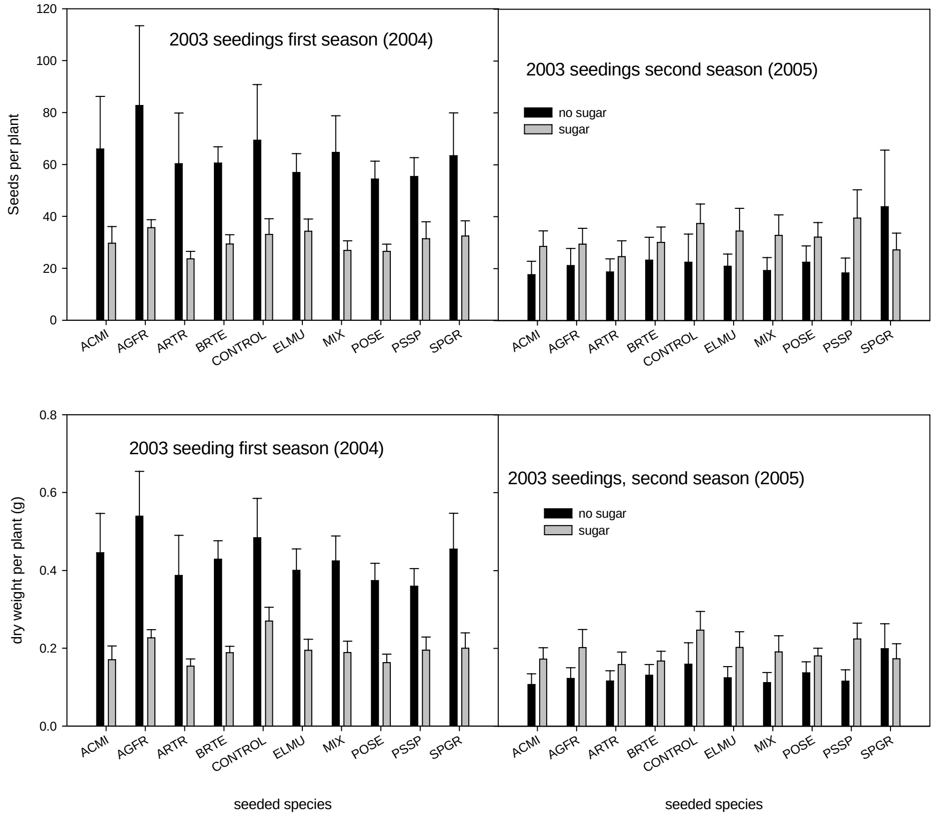

Fig. 6.6: Cheatgrass seeds per plant and weight per plant (+ SE) for 2003 seedings sampled in 2004 and 2005.

For 2004 seedings sampled in 2005 (*ie.* one season after sucrose application for the second iteration of the experiment), sucrose addition reduced weight per plant, weight per m^2, seeds per plant, and seeds per m^2. $F_{1,7}$ and p values were: 8.33, 0.028; 14.89, 0.008; 5.93, 0.05; and 14.22, 0.009 respectively. **Fig. 6.7** shows seeds and weight per m^2 for both 2003 and 2004 seedings sampled in 2005. The influence of sucrose addition on data scaled to a m^2 basis is stronger because sucrose not only reduced individual plant size and seed output in the 2004 seedings, but also reduced density (see **Fig. 6.5** and density results section).

Seedbank

Pre-seeding seed bank composition for each site is given in **Tables 6.2-6.9**. Across sites, the seed bank was dominated by annual species. Annual species comprised 87-100% of the seed bank in all sites, except for Lincoln Bench where the perennial species comprised 56% (**Fig. 6.8**).

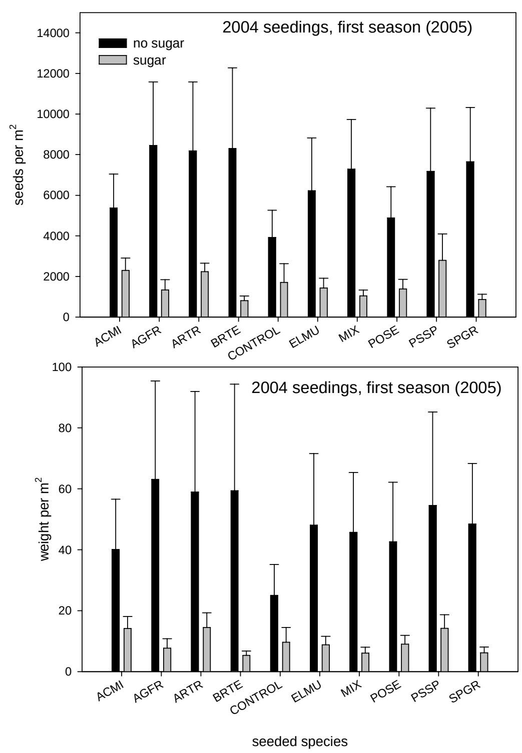

Fig. 6.7: Cheatgrass seeds per m^2 and weight per m^2 (+ SE) for 2004 seedings sampled in 2005.

Table 6.2. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Eden Valley, NV.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Shrubs							
Artemisia tridentata	Asteraceae	P	N			0.5	0.5
Grasses							
Poa secunda	Poaceae	P	N			0.5	0.5
Vulpia octoflora	Poaceae	A	N	33.8	8.9	11.0	3.6
Bromus tectorum	Poaceae	A	I	222.9	41.5	50.9	19.5
Unknown graminoid				1.0	0.7	1.8	1.1
Forbs							
Lomatiun nevadense	Apiaceae	P	N			1.4	1.4
Phlox gracilis	Polemoniaceae	A	N	24.8	6.2	22.0	5.1
Descurainia pinnata	Brassicaceae	A	N	1.4	0.8	17.4	4.9
Camissonia andina	Onagraceae	A	N	1.0	1.0	0.5	0.5
Gnaphalium spp.	Asteraceae		N	1.0	0.7	0.5	0.5
Collinsia parviflora	Scrophulariaceae	A	N			0.9	0.6
Gayophytum ramosissimum	Onagraceae	A	N			0.9	0.6
Mimulus suksdorfii	Scrophulariaceae	A	N			1.4	1.4
Draba verna	Brassicaceae	A	I	287.2	66.2	391.1	65.0
Sisymbrium altissimum	Brassicaceae	A	I	45.7	8.2	53.6	9.3
Erodium cicutarium	Geraniaceae	A	I	2.9	1.5	11.0	3.1
Ceratocephala testiculata	Ranunculaceae	A	I	1.9	0.9	1.8	1.1
Unknown forb				15.2	3.5	22.5	5.1

P=perennial, A= annual, N=native, I= introduced

Table 6.3. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Izzenhood Ranch, NV.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Shrubs							
Artemisia tridentata	Asteraceae	P	N			2.3	1.7
Grasses							
Vulpia octoflora	Poaceae	A	N	1.1	0.8	0.8	0.8
Bromus tectorum	Poaceae	A	I	171.6	26.0	17.1	4.0
Unknown				1.1	0.8		
Forbs							
Phlox gracilis	Polemoniaceae	A	N	225.4	33.3	42.7	8.3
Salsola iberica	Chenopodiaceae	A	I	134.0	52.3	91.5	43.6
Descurainia pinnata	Brassicaceae	A	N	3.4	1.8	41.9	9.6
Collinsia parviflora	Scrophulariaceae	A	N	2.8	1.9	3.1	1.9
Sisymbrium altissimum	Brassicaceae	A	I	2.8	1.5	2.3	1.3
Draba verna	Brassicaceae	A	I	0.6	0.6	9.3	3.2
Gnaphalium spp.	Asteraceae	A	N			1.6	1.1
Unknown forb				10.1	4.9	20.9	8.3

P=perennial, A= annual, N=native, I= introduced

Table 6.4. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Canyon Creek, ID.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Poa secunda	Poaceae	P	N	3.9	2.2	1.3	1.3
Pseudoroegneria spicata	Poaceae	P	N	5.2	2.6		
Taeniatherum caput-medusae	Poaceae	A	I	838.7	124.3	30.8	7.5
Bromus tectorum	Poaceae	A	I	20.8	5.1	1.3	1.3
Forbs							
Chondrilla juncea	Asteraceae	P	I			20.6	5.4
Helianthus annuus	Asteraceae	A	N	1.3	1.3	60.4	12.8
Draba verna	Brassicaceae	A	I			56.5	15.5
Holosteum umbellatum	Caryophyllaceae	A	I	2.6	2.6	29.6	21.5

P=perennial, A= annual, N=native, I= introduced

Table 6.5. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Cindercone Butte, ID.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Poa secunda	Poaceae	P	N	1.3	1.3		
Bromus tectorum	Poaceae	A	I	599.7	88.4	14.1	4.8
Taeniatherum caput-medusae	Poaceae	A	I	1.3	1.3		
Forbs							
Lithophragma glabrum	Saxifragaceae	P	N	26.2	18.6	59.1	41.6
Chondrilla juncea	Asteraceae	P	I			30.8	9.8
Myosurus apetalus	Ranunculaceae	A	N			18.0	6.6
Holosteum umbellatum	Caryophyllaceae	A	I	11.8	5.3	110.5	35.2
Draba verna	Brassicaceae	A	I			65.5	20.2
Sisymbrium altissimum	Brassicaceae	A	I	1.3	1.3	46.3	11.9
Lepidium perfoliatum	Brassicaceae	A	I			1.3	1.3
Unknown forb						9.0	4.2

P=perennial, A= annual, N=native, I= introduced

Table 6.6. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Lincoln Bench, OR.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Poa secunda	Poaceae	P	N	9.0	4.2	24.4	14.6
Pseudoroegneria spicata	Poaceae	P	N	1.3	1.3		
Vulpia octoflora	Poaceae	A	N			5.1	2.5
Taeniatherum caput-medusae	Poaceae	A	I	240.3	43.0	25.7	7.5
Bromus tectorum	Poaceae	A	I	114.4	20.3	6.4	2.8
Eremopyrum triticeum	Poaceae	A	I	6.4	3.4		
Forbs							
Lithophragma glabrum	Saxifragaceae	P	N	181.2	55.9	898.1	154.0
Chondrilla juncea	Asteraceae	P	I	5.1	3.1	9.0	6.6
Amsinckia tesselata	Boraginaceae	A	N			1.3	1.3
Helianthus annuus	Asteraceae	A	N			5.1	5.1
Myosurus apetalus	Ranunculaceae	A	N			1.3	1.3
Draba verna	Brassicaceae	A	I	2.6	2.6	402.2	106.0
Holosteum umbellatum	Caryophyllaceae	A	I	14.1	5.4	36.0	7.9
Amaranthus blitoides	Amaranthaceae	A	I	1.3	1.3	6.4	4.2
Sisymbrium altissimum	Brassicaceae	A	I			14.1	4.8
Ceratocephala testiculata	Ranunculaceae	A	I			3.9	2.9
Unknown forb						9.0	4.2

P=perennial, A= annual, N=native, I= introduced

Table 6.7. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Succor Creek, OR.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Poa secunda	Poaceae	P	N	2.6	1.8	5.1	2.5
Pseudoroegneria spicata	Poaceae	P	N				
Vulpia octoflora	Poaceae	A	N	3.9	3.9	1.3	1.3
Bromus tectorum	Poaceae	A	I	98.9	16.9	12.8	5.0
Eremopyrum triticeum	Poaceae	A	I	21.8	21.8	6.4	3.8
Forbs							
Myosurus apetalus	Ranunculaceae	A	N			231.3	70.3
Gnaphalium sp.	Asteraceae		N			1.3	1.3
Ceratocephala testiculata	Ranunculaceae	A	I	458.7	83.3	722.1	134.1
Amaranthus blitoides	Amaranthaceae	A	I	2.6	1.8	105.4	22.4
Holosteum umbellatum	Caryophyllaceae	A	I	5.1	2.5	19.3	9.7
Chorispora tenella	Brassicaceae	A	I			1.3	1.3
Draba verna	Brassicaceae	A	I			7.7	4.4
Lepidium perfoliatum	Brassicaceae	A	I			7.7	3.1
Unknown forb				11.6	9.1	1.3	1.3

P=perennial, A= annual, N=native, I= introduced

Table 6.8. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Vernon Hills, UT.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Bromus tectorum	Poaceae	A	I	144.5	43.2	33.2	7.6
Forbs							
Salsola kali	Chenopodiaceae	A	I	2045.8	503.5	2104.8	550.3
Ceratocephala testiculata	Ranunculaceae	A	I	7.5	5.3	6.6	4.8
Sisymbrium altissimum	Brassicaceae	A	I	1.2	1.2	4.0	4.0
Unknown forb				1.2	1.2		

P=perennial, A= annual, N=native, I= introduced

Table 6.9. Number of seeds (mean and standard error) by species in the soil surface and at the 0-5 cm depth in Simpson Springs, UT.

Species	Family	Growth form	Origin	Surface		0-5 cm	
				Mean (seeds m^{-2})	SE	Mean (seeds m^{-2})	SE
Grasses							
Bromus tectorum	Poaceae	A	I	43.7	18.1	34.7	8.9
Forbs							
Amaranthus albus	Amaranthaceae	A	N	3.9	2.9	25.7	15.5
Salsola kali	Chenopodiaceae	A	I	122.1	25.0	107.9	35.8
Ceratocephala testiculata	Ranunculaceae	A	I	334.1	67.1	52.7	15.7
Chenopodium album	Chenopodiaceae	A	I	1.3	1.3		
Unknown forb				6.4	3.4	14.1	5.4

P=perennial, A= annual, N=native, I= introduced

Seeds of the native shrubs were only found in the Nevada sites at very low densities (**Tables 6.2 and 6.3**). The only shrub species found was *Artemisia tridentata*. The lack of seeds of the native shrubs is not surprising given the absence of native shrubs at the study sites. Native perennial grasses, when present, were also found in low densities compared to the annual grasses.

Overall, exotic forbs and grasses dominated the seed bank. The relative contribution of exotic species to the seed bank can be observed in **Fig. 6.9**. Exotic annuals were present in all sites, and *Bromus tectorum* was the only species found in all locations, with the majority of the seeds located on the soil surface. In addition to *B. tectorum*, the introduced annuals *Ceratocephala testiculata* and *Sisymbrium altissimum* were commonly found.

Vernon Hills is the site with the lowest number of species and it was the only site where native species were not recorded (**Table 6.8**). This seedbank was dominated by *Salsola kali*.

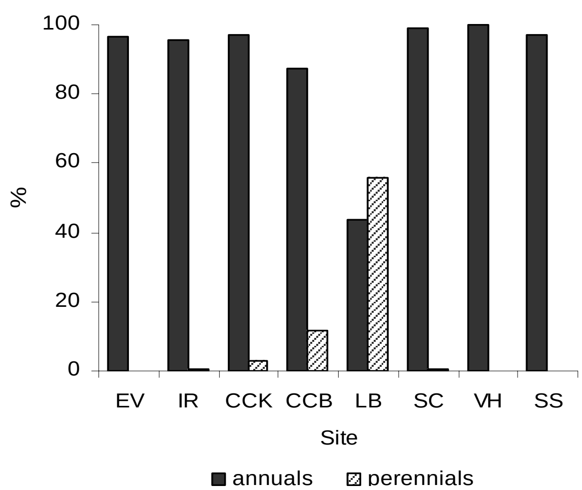

Fig. 6.8: relative contribution (%) of annuals species to the seed bank by site. EV = Eden Valley, NV; IR = Izzenhood Ranch, NV; CCK = Canyon Creek, ID; CCB = Cindercone Butte, ID; LB = Lincoln Bench, OR; SC = Succor Creek, OR; VH = Vernon Hills, UT; SS = Simpson Springs, UT.

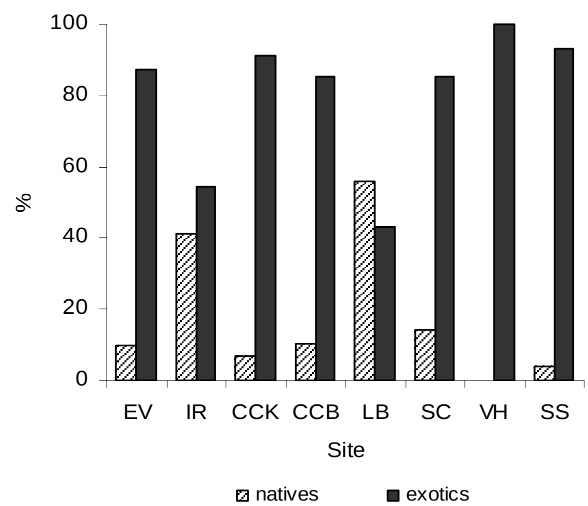

Fig. 6.9. Relative contribution (%) of natives and exotics seeds to the seed bank by site. Site abbreviations are the same as those for **Fig. 6.8.**

The seedbank composition reflected the aboveground composition of the plant community which is mainly dominated by annual species. In general, species with the largest contributions to the seed bank dominated the aboveground vegetation during the study period (personal observations).

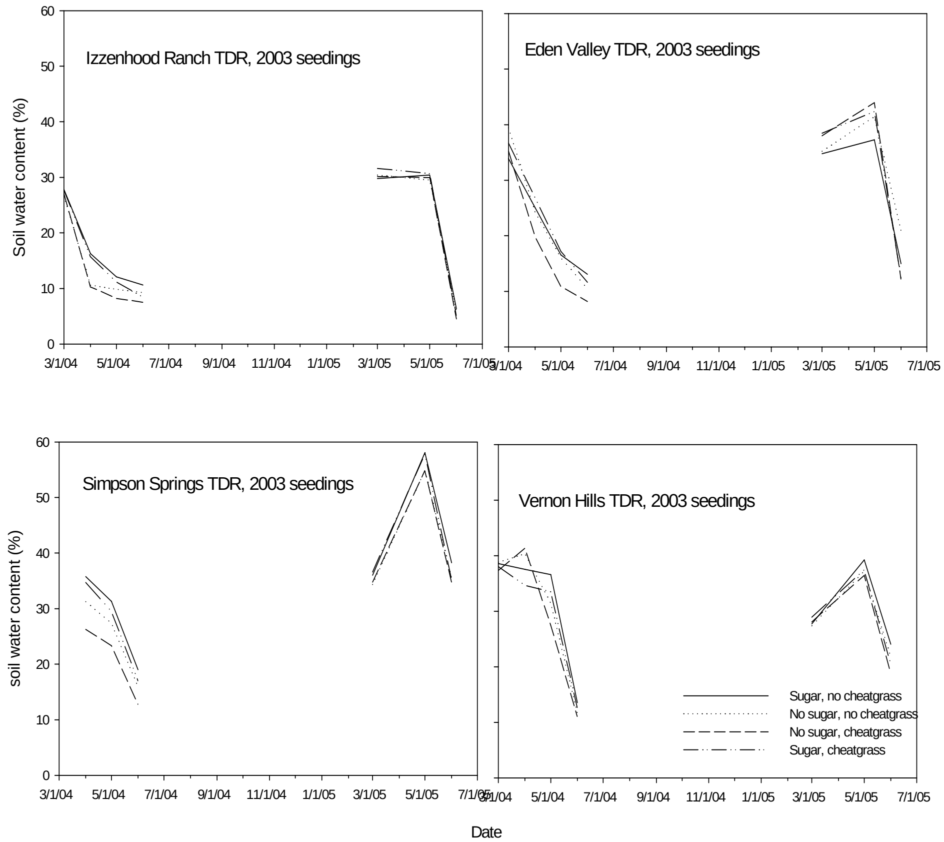

Fig. 6.10. Soil moisture measured by hand-held TDR at Nevada (top graphs) and Utah (bottom graphs) sites from 2004-2005. Left graphs are low precipitation sites, and right graphs are high precipitation sites.

Soil Moisture

Soil moisture for 2004 and 2005 growing seasons at the NV and UT sites, as measured by hand-held TDR probe, is presented in **Fig. 6.10**. The data presented here are only from the plots seeded in 2003. Mixed-model ANOVA (sites as blocks) conducted on log-transformed data from June 2004 showed that after the first growing season, cheatgrass significantly lowered soil moisture ($F_{1, 299}$ 70.93, P<0.0001). The effect of sucrose addition was marginally significant (and statistical power was very low), indicating that sugar-treated plots had increased soil moisture ($F_{1, 2}$ = 15.26, p = 0.059) possibly due to the negative effect of sucrose on plant growth (and thus water use). Soil moisture did not differ between low and high precipitation zones, but there was a significant cheatgrass by precipitation interaction ($F_{1, 299}$ 5.61, p=0.019). The interaction occurred because there was no significant effect of cheatgrass presence or absence on soil moisture at the high precipitation sites, but at the low precipitation sites removal of cheatgrass resulted in higher soil moisture. No other factors or interactions were significant.

DISCUSSION

Chapter 4 (soil nutrient analyses) shows that the sucrose addition did alter soil nitrogen and phosphorus in the short term, and indicates that soil fertility declined through the course of the study so that by the second season after application there was no difference between sucrose treated and untreated plots.

Sucrose addition also reduced cheatgrass seed output and biomass in the first season after application, and consequently resulted in reduced cheatgrass density in subsequent seasons. However cheatgrass seed production was generally high, and even in carbon-amended plots the initial 300 PLS m^{-2} seed rate of cheatgrass resulted in as many as 20,000 seeds per m^2 produced by 2005 (**Fig. 6.7**). Because the sucrose effect was short-lived, possibly applying sucrose two seasons in a row would suppress cheatgrass more successfully.

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Appendix 6.1: target species densities through the course of the study. Blank cells indicate missing or uncollected data.

Canyon Creek, ID				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	16.33333	7.505553	12.33333	6.790422			24.16667	11.81854	8.333333	6.370505
			SUGAR	12	7.81025	13.33333	6.788737			0	0	3.666667	4.725816
2	ACMI	YES	NO SUGAR			5.5	8.262047			18.5	16.54386	0.333333	0.57735
			SUGAR			11.16667	4.696061			1.333333	0.57735	10	11.16915
3	ARTR	NO	NO SUGAR	27.66667	17.89786	23	16.09517			2.333333	0.763763	0.666667	1.154701
			SUGAR	12.66667	2.516611	3.833333	2.566538			0	0	0	0
4	ARTR	YES	NO SUGAR			6.666667	6.754625			4.833333	3.695745	0.666667	0.57735
			SUGAR			3.5	1.341113			0	0	0.666667	1.154701
6	CONTROL	YES	NO SUGAR	0	0	0.166667	0.288675			0	0	0	0
			SUGAR	0	0	0.5	0.866025			0	0	0.333333	0.57735
7	ELMU	NO	NO SUGAR	3.666667	3.21455	1.5	2.598076			7.833333	4.516539	2.666667	0.57735
			SUGAR	6	4.358899	2.5	2.785831			12.66667	4.429733	4.166667	3.329164
8	ELMU	YES	NO SUGAR			2.666667	2.484209			4.833333	2.020726	5.666667	1.527525
			SUGAR			0.833333	1.443376			6.833333	1.341113	1.333333	1.258306
9	MIX	NO	NO SUGAR	16.66667	6.806859	14.16667	2.568358			37	8.451575	13.33333	1.527525
			SUGAR	10.33333	9.073772	7.5	3.621214			9.5	5.323258	10.83333	8.129166
10	MIX	YES	NO SUGAR	8	5.196152	4.333333	2.081666			8.833333	5.670634	4	2
			SUGAR	10.33333	6.806859	2.666667	1.629788			4	1.527525	0.333333	0.288675
11	POSE	NO	NO SUGAR	6	6.557439	8.5	8.642206			38.16667	29.8762	33.66667	15.54295
			SUGAR	0	0	8.833333	3.061559			2	2.104876	14.33333	6.934215
12	POSE	YES	NO SUGAR			3.333333	2.291288			25	29.15995	12.33333	17.60918
			SUGAR			3.166667	1.540833			1.166667	0.763763	0.166667	0.288675
13	PSSP	NO	NO SUGAR	37.33333	17.09776	6.166667	2.363709			112.8333	35.78624	24.83333	3.013857
			SUGAR	36.33333	25.92939	3	1.618183			41.66667	31.30886	3.666667	3.329164
14	PSSP	YES	NO SUGAR			2.333333	2.363709			26.66667	9.865196	23	13.53699
			SUGAR			1.333333	1.527525			17	6.384215	2.166667	3.329164
15	SPGR	NO	NO SUGAR	0	0	1	1			2.666667	2.929733	0.333333	0.57735
			SUGAR	0	0	0.833333	1.443376			1.666667	1.607275	0.666667	0.763763
16	SPGR	YES	NO SUGAR			1	0.866025			0.5	0.5	0	0
			SUGAR			1.166667	0.763763			0.5	0.5	0	0
17	AGFR	NO	NO SUGAR	0	0	34.83333	6.508326			43.33333	18.50424	24.16667	6.898067
			SUGAR	0	0	38.5	21.15665			6.333333	4.125601	16.33333	11.40541
18	AGFR	YES	NO SUGAR	0	0	19.33333	10.44981			16	9.102667	12	2.291288
			SUGAR	0	0	19	6.953613			4.833333	4.444263	10.33333	16.61576

Cindercone Butte, ID				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	1.666667	0.57735	0.5	0			105.3333	90.96336	4.666667	4.072264
			SUGAR	4.666667	3.785939	5.666667	4.804512			1.833333	1.755942	7.833333	8.892881
2	ACMI	YES	NO SUGAR			0.666667	1.154701			42.16667	32.87223	0	0
			SUGAR			2.333333	2.362908			0.666667	0.57735	2.333333	4.041452
3	ARTR	NO	NO SUGAR	4.333333	5.859465	0.166667	0.288675			1.333333	2.309401	0	0
			SUGAR	5.666667	6.429101	0.333333	0.288675			0	0	0	0
4	ARTR	YES	NO SUGAR			0	0			0.333333	0.57735	0	0
			SUGAR			0	0			0.166667	0.288675	0	0
6	CONTROL	YES	NO SUGAR	0	0	0	0			0	0	0	0
			SUGAR	0	0	0.166667	0.288675			0.333333	0.57735	0	0
7	ELMU	NO	NO SUGAR	0.666667	1.154701	0	0			8	4.330127	3.666667	1.154701
			SUGAR	1.333333	1.527525	0.166667	0.288675			2.5	0.5	0	0
8	ELMU	YES	NO SUGAR			1.5	2.598076			3	1.802776	3.166667	1.258306
			SUGAR			1.833333	2.362908			3.166667	1.755942	0	0
9	MIX	NO	NO SUGAR	4.333333	4.932883	1.166667	1.258306			23.66667	20.25051	4.166667	1.892969
			SUGAR	1.666667	0.57735	2.833333	1.443376			5.666667	4.368447	1.333333	1.154701
10	MIX	YES	NO SUGAR	2.666667	3.05505	2.166667	1.040833			4.833333	3.511885	1.166667	1.258306
			SUGAR	5.333333	3.21455	2.166667	0.763763			4.666667	4.752192	2	3.464102
11	POSE	NO	NO SUGAR	3.666667	1.527525	6.166667	5.484828			30.33333	35.27511	20	17.38534
			SUGAR	0.666667	1.154701	4.833333	0.763763			0.166667	0.288675	1.666667	1.607275
12	POSE	YES	NO SUGAR			3.166667	2.516611			12.66667	7.371115	2.666667	1.755942
			SUGAR			5.833333	4.536886			0	0	0.666667	0.763763
13	PSSP	NO	NO SUGAR	1.333333	0.57735	0.666667	0.288675			54.66667	22.18859	20	7.81025
			SUGAR	4	4.358899	0.5	0.5			34.16667	26.2504	0	0
14	PSSP	YES	NO SUGAR			5.333333	2.565801			15.83333	15.33243	0.5	0.5
			SUGAR			0.333333	0.288675			10.5	8.674676	0	0
15	SPGR	NO	NO SUGAR	0	0	0.5	0			0.5	0.866025	0	0
			SUGAR	0	0	0.166667	0.288675			0	0	0.333333	0.57735
16	SPGR	YES	NO SUGAR			0.666667	0.763763			0.5	0.5	0	0
			SUGAR			0.333333	0.288675			0.333333	0.57735	0	0
17	AGFR	NO	NO SUGAR	0	0	12	1.802776			10.33333	4.752192	4	2.645751
			SUGAR	0	0	15	9.165151			2.166667	0.763763	0.333333	0.57735
18	AGFR	YES	NO SUGAR	0	0	7.666667	6.525591			15.66667	16.50253	5.166667	5.965177
			SUGAR	0	0	9.5	2.783882			2.833333	1.040833	0	0

Izzenhood Ranch, NV				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	31	15.52417	10.5	11.6297	0	0	6.5	9.124144	0	0
			SUGAR	31.33333	12.8582	21.83333	15.27525	1	1.732051	3.666667	1.607275	0	0
2	ACMI	YES	NO SUGAR	15.66667	12.58306	2	1.802776	0.333333	0.57735	22.33333	8.036376	0	0
			SUGAR	12	4	7	4.924429	1	1.732051	40	54.05784	0	0
3	ARTR	NO	NO SUGAR	107	22.6495	63.5	5.408327	30.33333	3.05505	41.83333	28.35636	1	1.732051
			SUGAR	84	31.74902	54.16667	7.421815	24.66667	7.637626	26.66667	31.08188	0	0
4	ARTR	YES	NO SUGAR	72	21	40.5	9.836158	15	9.643651	35	4.330127	0	0
			SUGAR	94.33333	26.55811	54.5	15.13275	20.33333	3.21455	30.16667	27.20907	0.333333	0.57735
6	CONTROL	YES	NO SUGAR	0.333333	0.57735	0	0	0	0	0	0	0	0
			SUGAR	0	0	1.5	2.598076	0	0	0	0	0	0
7	ELMU	NO	NO SUGAR	34.33333	4.932883	3.833333	4.072264	2.666667	3.05505	33.83333	13.0416	0	0
			SUGAR	40.66667	11.59023	11.16667	9.517528	2	2.645751	21	3.774917	0	0
8	ELMU	YES	NO SUGAR	24	7.937254	0.833333	1.040833	0	0	14.83333	6.788471	0	0
			SUGAR	31	7.549834	2	1	0.666667	0.57735	22	16.7556	0	0
9	MIX	NO	NO SUGAR	61	19.07878	25.83333	2.84312	14.33333	3.785939	52.66667	15.11897	2	1
			SUGAR	45.66667	13.01281	16.83333	4.481443	9	2	32.83333	16.74316	2.666667	1.527525
10	MIX	YES	NO SUGAR	43	9.539392	11.5	4.330127	7	6.557439	25.16667	20.26286	3.333333	5.773503
			SUGAR	46.66667	10.69268	10.16667	1.755942	11.66667	5.033223	19	9.367497	1.333333	1.154701
11	POSE	NO	NO SUGAR	12	5.291503	14.5	6.614378	2.333333	0.57735	27.83333	24.11604	16.66667	6.429101
			SUGAR	0	0	1	1.322876	0	0	6.833333	4.907477	11.33333	5.033223
12	POSE	YES	NO SUGAR	0.666667	1.154701	2.166667	2.254625	0	0	22.16667	13.01281	21.33333	12.34234
			SUGAR	0.666667	0.57735	1.666667	2.081666	0	0	5.666667	2.081666	4.666667	6.429101
13	PSSP	NO	NO SUGAR	89.33333	20.59935	2	1.322876	1	1	140.8333	40.99187	0	0
			SUGAR	126.3333	33.54599	0.833333	1.040833	0	0	79.66667	18.4549	0	0
14	PSSP	YES	NO SUGAR	39	27.51363	0.833333	1.443376	0	0	40.83333	30.6159	0	0
			SUGAR	132.3333	47.71094	0	0	0	0	41.5	28.61818	0	0
15	SPGR	NO	NO SUGAR	0	0	0	0	0	0	0.666667	0.288675	0	0
			SUGAR	0	0	0	0	0	0	1	1	0	0
16	SPGR	YES	NO SUGAR	0	0	0	0	0	0	0	0	0	0
			SUGAR	0.666667	1.154701	0.333333	0.57735	0.666667	1.154701	0.5	0.866025	0	0
17	AGFR	NO	NO SUGAR	46.33333	20.98412	19.33333	7.973916	2	2	27.5	11.71537	6	5.567764
			SUGAR	34.33333	30.43572	20.5	5.291503	2	1.732051	17	3.278719	15.33333	11.54701
18	AGFR	YES	NO SUGAR	28.66667	7.767453	2.5	1.802776	0.333333	0.57735	12.83333	6.448514	0.666667	1.154701
			SUGAR	31	15.52417	10.5	11.6297	0	0	6.5	9.124144	0	0

Eden Valley, NV				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	4	4	1.333333	2.309401	0	0	19	10.58301	0	0
			SUGAR	11.66667	10.2632	1.833333	2.753785	0	0	6.5	6.946222	0	0
2	ACMI	YES	NO SUGAR	65	12.16553	2.833333	3.617089	0	0	9.5	8.351647	33	57.15768
			SUGAR	6.666667	2.081666	3.166667	4.618802	0	0	6.333333	4.072264	0.333333	0.57735
3	ARTR	NO	NO SUGAR	7.333333	11.01514	0	0	0	0	15.5	9.5	0	0
			SUGAR	5.333333	5.507571	0	0	0	0	14.5	8.674676	0	0
4	ARTR	YES	NO SUGAR	33	13	0	0	0	0	10.5	6.946222	0	0
			SUGAR	20.66667	5.131601	0.166667	0.288675	0	0	10.16667	7.767453	0	0
6	CONTROL	YES	NO SUGAR	0	0	0	0	0	0	0	0	0	0
			SUGAR	0	0	0	0	0	0	0	0	0	0
7	ELMU	NO	NO SUGAR	14.66667	7.371115	0.5	0.5	0	0	15.16667	9.751068	0	0
			SUGAR	19.33333	9.291573	0.333333	0.57735	0.333333	0.57735	14.66667	5.251984	0	0
8	ELMU	YES	NO SUGAR	18	4.582576	1.666667	1.258306	1.666667	0.57735	11.5	1.802776	1.666667	2.886751
			SUGAR	14.66667	1.527525	1.666667	1.258306	2.333333	2.516611	17	7.794229	0.333333	0.57735
9	MIX	NO	NO SUGAR	11	5.291503	1	0.866025	0	0	24.83333	10.72769	1	1.732051
			SUGAR	4.666667	4.725816	0.666667	1.154701	0	0	14	4.444097	0.166667	0.288675
10	MIX	YES	NO SUGAR	14.66667	5.773503	1.166667	2.020726	0.666667	1.154701	20.5	9.5	0.333333	0.57735
			SUGAR	22.33333	8.082904	0.666667	0.288675	0.666667	1.154701	13.16667	6.429101	0.166667	0.288675
11	POSE	NO	NO SUGAR	25	31.19295	7.166667	7.815583	3	5.196152	26.5	13.44433	6.5	3.041381
			SUGAR	1.333333	2.309401	2.833333	0.763763	0.666667	1.154701	2.833333	3.685557	0.5	0
12	POSE	YES	NO SUGAR	4	6.082763	4.833333	4.536886	0	0	13.16667	8.401389	1	0.5
			SUGAR	0	0	0	0	0	0	1.666667	1.040833	0.166667	0.288675
13	PSSP	NO	NO SUGAR	33	7.81025	1.833333	2.020726	0.666667	1.154701	22.33333	18.536	0.166667	0.288675
			SUGAR	36	11.78983	0.333333	0.57735	0	0	51.83333	12.08649	0.166667	0.288675
14	PSSP	YES	NO SUGAR	25.66667	9.865766	1.333333	1.258306	1	1	22	22.95103	1.666667	2.886751
			SUGAR	41.66667	14.29452	0.333333	0.57735	0	0	22.83333	6.751543	0.333333	0.288675
15	SPGR	NO	NO SUGAR	0	0	0	0	0	0	0.333333	0.288675	0.166667	0.288675
			SUGAR	0	0	0	0	0	0	0	0	0.5	0.866025
16	SPGR	YES	NO SUGAR	0	0	0	0	0	0	0.166667	0.288675	0	0
			SUGAR	0	0	1.666667	2.886751	0	0	0.333333	0.57735	0	0
17	AGFR	NO	NO SUGAR	7.666667	9.073772	4.666667	2.929733	0	0	26.16667	16.07275	5	7.399324
			SUGAR	12.66667	1.154701	14.66667	7.00595	0	0	10.5	7.26292	1.166667	1.607275
18	AGFR	YES	NO SUGAR	12.33333	4.041452	5	4.330127	0	0	9.166667	6.751543	0	0
			SUGAR	43.66667	13.20353	4.5	1.802776	1.666667	0.57735	12.16667	5.619905	13.66667	17.78576

Lincoln Bench, OR				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	30	25.98076	22.16667	16.18881			5.166667	8.520949	6.833333	10.53961
			SUGAR	39	12.12436	18.66667	8.557289			14.33333	23.9667	25.66667	19.31537
2	ACMI	YES	NO SUGAR			3.333333	4.575171			1.166667	1.040833	0.166667	0.288675
			SUGAR			17.33333	3.445988			1.5	1.89595	6.5	9.539392
3	ARTR	NO	NO SUGAR	6.666667	2.516611	6.5	1.835656			0.833333	1.443376	0	0
			SUGAR	18.66667	13.79613	15	11.32708			0.166667	0.288675	0	0
4	ARTR	YES	NO SUGAR			21.33333	2.809401			0.5	0.866025	0	0
			SUGAR			2.833333	3.34312			0	0	0	0
6	CONTROL	YES	NO SUGAR	0	0	0	0			0	0	0.5	0.866025
			SUGAR	0	0	0	0			0	0	0.166667	0.288675
7	ELMU	NO	NO SUGAR	17.66667	3.21455	1.666667	0.788675			18.33333	11.03604	15.83333	11.57944
			SUGAR	16.66667	9.814955	1.833333	1.07735			14.5	14.73104	10.83333	14.64866
8	ELMU	YES	NO SUGAR			5.666667	1.527525			8.833333	4.45877	7.333333	5.346338
			SUGAR			7.833333	3.027525			7.333333	6.481758	1.833333	2.753785
9	MIX	NO	NO SUGAR	17	12.12436	12.16667	12.51965			23.83333	14.46075	14.33333	3.685557
			SUGAR	22	11.13553	10.83333	6.794158			12.16667	15.49494	12	5.291503
10	MIX	YES	NO SUGAR	23.66667	15.53491	4.5	3.050651			5.5	4.927095	2.666667	2.081666
			SUGAR	25.66667	2.516611	5	3.122499			6.5	6.833549	2.833333	2.565801
11	POSE	NO	NO SUGAR	36	33.04542	3.5	3.179449			55.66667	49.42096	51.66667	41.25025
			SUGAR	1.666667	2.081666	2	1.546981			23	36.8295	18.83333	25.00667
12	POSE	YES	NO SUGAR			0	0			19.16667	23.45056	9.333333	8.386497
			SUGAR			2.666667	4.209627			4.666667	8.082904	6.666667	8.144528
13	PSSP	NO	NO SUGAR	27.66667	23.15887	6.833333	6.941312			51.83333	33.58308	11.16667	17.22159
			SUGAR	48.33333	39.57693	4.166667	4.696579			32.83333	25.3549	4.833333	5.619905
14	PSSP	YES	NO SUGAR			0	0			7.666667	8.051855	4	3.5
			SUGAR			2	1.527525			11	8.233798	0.333333	0.57735
15	SPGR	NO	NO SUGAR	0.333333	0.57735	0.333333	0.57735			0	0	2	1.5
			SUGAR	0	0	0	0			0.166667	0.288675	1.833333	2.020726
16	SPGR	YES	NO SUGAR			0	0			0.333333	0.57735	1.333333	2.309401
			SUGAR			0	0			0	0	5.5	6.383573
17	AGFR	NO	NO SUGAR	0	0	13.33333	11.15536			29	17.33362	19	6.383573
			SUGAR	0	0	12.33333	12.43051			28.83333	40.38841	23.5	18.66146
18	AGFR	YES	NO SUGAR	0	0	6.166667	4.466441			6.333333	5.243935	7.833333	5.838093
			SUGAR	0	0	1.666667	2.886751			9.333333	11.48705	8.5	7.697402

Succor Creek, OR				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	0	0	3	4.358899			1.833333	1.900226	34.33333	17.13427
			SUGAR	0.333333	0.57735	0.583333	1.010363			23.33333	30.25963	3.833333	4.481443
2	ACMI	YES	NO SUGAR			0.666667	0.763763			2.666667	4.618802	0.166667	0.288675
			SUGAR			0	0			5.5	5.766281	0.833333	1.443376
3	ARTR	NO	NO SUGAR	0.333333	0.57735	0	0			0.5	0.5	0	0
			SUGAR	3.333333	4.041452	0	0			0	0	0	0
4	ARTR	YES	NO SUGAR			0	0			0	0	0	0
			SUGAR			0.666667	1.154701			0	0	0	0
6	CONTROL	YES	NO SUGAR	0	0	0	0			0	0	0	0
			SUGAR	0	0	0	0			0.5	0.866025	1.166667	2.020726
7	ELMU	NO	NO SUGAR	8	2.645751	0	0			7.166667	3.520726	0	0
			SUGAR	6.666667	3.21455	1.166667	2.020726			6.833333	3.065801	0	0
8	ELMU	YES	NO SUGAR			0	0			1.666667	1.154701	0	0
			SUGAR			0.333333	0.57735			3.666667	1.527525	0.333333	0.57735
9	MIX	NO	NO SUGAR	2.333333	1.527525	0.833333	1.040833			5.666667	3.974233	1.666667	0.57735
			SUGAR	4.333333	2.886751	1.166667	0.763763			9.166667	7.187776	12.66667	8.386497
10	MIX	YES	NO SUGAR	5.666667	2.081666	3.5	3.776668			1	1.732051	0	0
			SUGAR	6	1.732051	1.833333	3.175426			4.833333	6.139955	1.166667	2.020726
11	POSE	NO	NO SUGAR	2.333333	2.081666	8.666667	5.932226			9	11.3123	11	0
			SUGAR	5	4.582576	16.66667	10.91276			26.5	18.12943	22	2.645751
12	POSE	YES	NO SUGAR			1	1.329508			5	6.553876	0.5	0.5
			SUGAR			2.333333	1.906858			6.833333	7.654016	1.333333	1.258306
13	PSSP	NO	NO SUGAR	5.666667	5.507571	0.666667	0.763763			10.83333	7.182341	0	0
			SUGAR	8	2	0.666667	0.788675			31.16667	27.86989	0.166667	0.288675
14	PSSP	YES	NO SUGAR			0.166667	0.288675			10.16667	5.653127	0.166667	0.288675
			SUGAR			0	0			7	8.535031	0.666667	1.154701
15	SPGR	NO	NO SUGAR	0	0	0	0			1.166667	0.57735	0.333333	0.57735
			SUGAR	0.333333	0.57735	0	0			2	2.291288	0	0
16	SPGR	YES	NO SUGAR			0	0			2	2.179449	0	0
			SUGAR			0.166667	0.288675			0.833333	1.443376	0	0
17	AGFR	NO	NO SUGAR	0	0	14.66667	9.776691			3.833333	5.39586	3.833333	2.753785
			SUGAR	0	0	17.33333	17.30001			4.666667	7.216878	9.833333	6.525591
18	AGFR	YES	NO SUGAR	0	0	4.5	2.598076			1.5	1.322876	0	0
			SUGAR	0	0	2.666667	2.086638			2	2.020726	2.166667	2.254625

Simpson Springs, UT				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	1	1.732051	7.166667	4.25245	2	2	2.333333	2.309401	3	5.196152
			SUGAR	0	0	11.83333	11.29528	0.333333	0.57735	2.833333	3.685557	0.5	0.5
2	ACMI	YES	NO SUGAR	0	0	2.166667	1.040833	0	0	6	4.092676	1	1
			SUGAR	0	0	5.166667	4.481443	2.333333	2.516611	1.666667	2.466441	0.833333	0.288675
3	ARTR	NO	NO SUGAR	0.333333	0.57735	0	0	0	0	3.666667	2.84312	12.16667	3.40343
			SUGAR	0	0	0.166667	0.288675	0.333333	0.57735	4.833333	3.05505	17	16.30184
4	ARTR	YES	NO SUGAR	2	3.464102	1.166667	2.020726	0	0	14.33333	4.481443	29.83333	30.25861
			SUGAR	0	0	0	0	0	0	6.5	7.794229	22	12.75735
6	CONTROL	YES	NO SUGAR	0.333333	0.57735	9.166667	13.27906	0	0	0.333333	0.57735	2.666667	4.193249
			SUGAR	0	0	3.666667	0.763763	1.333333	1.527525	4.333333	2.929733	2.166667	3.329164
7	ELMU	NO	NO SUGAR	10.33333	2.081666	8	1.802776	5.333333	4.725816	4	2	0.333333	0.288675
			SUGAR	23.33333	13.31666	17.16667	6.429101	9.333333	3.21455	0.5	0.5	1.166667	1.258306
8	ELMU	YES	NO SUGAR	7.333333	7.571878	21.5	8.674676	7.333333	7.505553	5.166667	3.785939	1.666667	1.527525
			SUGAR	17.66667	19.13984	16.16667	14.1892	17	6	0.833333	0.288675	0.333333	0.288675
9	MIX	NO	NO SUGAR	23.33333	21.22106	24.66667	5.619905	5.333333	6.658328	11.66667	6.00694	10.33333	7.751344
			SUGAR	19	10.14889	8.666667	1.755942	6	0	32.33333	37.52444	10.5	2
10	MIX	YES	NO SUGAR	21.33333	3.05505	20.83333	9.569918	7.666667	6.506407	6.833333	3.685557	3	0.866025
			SUGAR	22.33333	2.309401	20.16667	10.75097	6.666667	8.326664	6	3	7.166667	7.973916
11	POSE	NO	NO SUGAR	12.33333	21.36196	35.66667	25.54082	2	1.732051	3.333333	4.072264	10.83333	3.785939
			SUGAR	0	0	34.5	18.3303	9	1.732051	3.833333	4.536886	5	3.774917
12	POSE	YES	NO SUGAR	2.333333	4.041452	32.16667	39.73139	0.333333	0.57735	8	12.57975	13.66667	10.153
			SUGAR	0	0	21.83333	19.25054	0	0	4.666667	6.429101	1.166667	0.763763
13	PSSP	NO	NO SUGAR	72	23.64318	46.83333	14.18039	16.66667	17.55942	13.33333	10.8896	0.666667	1.154701
			SUGAR	49.66667	33.00505	27.66667	9.237604	12.66667	6.506407	23	16.88935	2.166667	2.081666
14	PSSP	YES	NO SUGAR	52.33333	28.72862	40.66667	6.525591	21.33333	4.932883	43.33333	21.65833	1.833333	1.755942
			SUGAR	90.33333	62.68439	33.33333	13.20353	23.33333	14.57166	33.16667	27.46513	1.333333	1.258306
15	SPGR	NO	NO SUGAR	0.333333	0.57735	0.333333	0.57735	2.666667	4.618802	0.833333	0.763763	0.833333	1.443376
			SUGAR	1.333333	2.309401	1.5	2.179449	1	1.732051	0	0	1.333333	1.040833
16	SPGR	YES	NO SUGAR	0.333333	0.57735	1.166667	0.763763	0.666667	0.57735	1	1	0.833333	0.763763
			SUGAR	0	0	0.833333	0.288675	0.333333	0.57735	0	0	2	2
17	AGFR	NO	NO SUGAR	11	10.81665	14.66667	6.601767	5.666667	2.516611	7.666667	3.685557	2.166667	2.929733
			SUGAR	7	6.082763	16.33333	8.607168	3.333333	4.041452	9.166667	3.752777	5.833333	1.258306
18	AGFR	YES	NO SUGAR	11.66667	8.020806	20.5	8.261356	10	5.196152	10.16667	12.00347	2	3.041381
			SUGAR	3.333333	2.081666	10.83333	6.251666	6	5.291503	0.833333	0.763763	4	2.179449

Vernon Hills, UT				*Seed year 2003*						*Seed year 2004*			
N=3 in all cases				2004		2005		2006		2005		2006	
Plot	Species	Cheatgrass	treatment	Density	SD	Density	SD	Density	SD	Density	SD	Density	SD
1	ACMI	NO	NO SUGAR	9.333333	3.785939	6.666667	3.511885	1.333333	2.309401	0.333333	0.57735	2	1.802776
			SUGAR	4.666667	6.350853	2.333333	3.21455	0	0	0	0	0.5	0.866025
2	ACMI	YES	NO SUGAR	12.33333	4.163332	5.833333	1.892969	0	0	0	0	0.833333	1.443376
			SUGAR	0.666667	1.154701	0.166667	0.288675	0.333333	0.57735	0.166667	0.288675	1.666667	2.886751
3	ARTR	NO	NO SUGAR	17.66667	4.041452	13.16667	5.204165	0	0	5.833333	4.645787	0	0
			SUGAR	37.66667	19.29594	16.33333	7.522189	0	0	0.666667	1.154701	0.166667	0.288675
4	ARTR	YES	NO SUGAR	22	13.85641	13.16667	4.856267	0	0	0.5	0.866025	0	0
			SUGAR	43.33333	7.094599	24.5	2.179449	4.333333	7.505553	2.833333	4.481443	2.5	4.330127
6	CONTROL	YES	NO SUGAR	0.666667	1.154701	0.166667	0.288675	0	0	0	0	0.166667	0.288675
			SUGAR	0.666667	1.154701	0.333333	0.57735	0	0	0	0	0	0
7	ELMU	NO	NO SUGAR	0.333333	0.57735	0	0	0	0	0.166667	0.288675	0.333333	0.57735
			SUGAR	0.666667	1.154701	0.666667	1.154701	0	0	0	0	0	0
8	ELMU	YES	NO SUGAR	5.666667	2.516611	1.833333	0.763763	2	0	0.5	0.866025	0.666667	1.154701
			SUGAR	1.666667	2.886751	0.333333	0.57735	0.333333	0.57735	0.166667	0.288675	0.166667	0.288675
9	MIX	NO	NO SUGAR	10.66667	5.507571	6.5	3.278719	0.333333	0.57735	0.166667	0.288675	1.333333	1.258306
			SUGAR	10	2	4.333333	1.443376	0	0	0.166667	0.288675	3.666667	4.618802
10	MIX	YES	NO SUGAR	24	13.22876	6.5	4.358899	0.333333	0.57735	0.166667	0.288675	0.5	0.5
			SUGAR	6.333333	4.163332	2.833333	2.020726	0	0	0.333333	0.288675	0.666667	1.154701
11	POSE	NO	NO SUGAR	2.333333	4.041452	7.5	7	0	0	0	0	1	1
			SUGAR	0.333333	0.57735	5.666667	5.008326	0.333333	0.57735	0.166667	0.288675	1.666667	2.886751
12	POSE	YES	NO SUGAR	0	0	1.5	2.179449	0.333333	0.57735	0.666667	0.57735	3.5	3.278719
			SUGAR	0	0	0.333333	0.57735	0	0	0	0	0.833333	1.443376
13	PSSP	NO	NO SUGAR	10.33333	5.033223	4	5.678908	0.666667	0.57735	2	3.041381	0	0
			SUGAR	18.33333	8.621678	0.166667	0.288675	0	0	0.5	0.866025	0	0
14	PSSP	YES	NO SUGAR	25.33333	15.17674	12.83333	7.094599	3.333333	3.511885	2	1.732051	0.333333	0.57735
			SUGAR	6	2.645751	0.722222	0.751542	1	1.732051	4	5.634714	0	0
15	SPGR	NO	NO SUGAR	1.333333	1.527525	1.333333	1.892969	0	0	0	0	0	0
			SUGAR	5.333333	4.725816	4.333333	4.041452	0	0	0	0	0	0
16	SPGR	YES	NO SUGAR	1	1.732051	0.666667	0.57735	0	0	0	0	0	0
			SUGAR	0	0	0	0	0	0	0.25	0.353553	0	0
17	AGFR	NO	NO SUGAR	2.333333	3.21455	1.916667	0.589256	0.25	0.353553	0.111111	0.19245	1.166667	1.607275
			SUGAR	0.333333	0.57735	3.166667	5.057997	2.333333	2.081666	0	0	0	0
18	AGFR	YES	NO SUGAR	3.666667	3.21455	4.222222	1.677741	2.5	2.12132	1.166667	1.130388	0.5	0.866025
			SUGAR	1.666667	0.57735	5.5	4.821825	1.333333	0.57735	0	0	2.666667	3.05505

Chapter 7 – Experiment 2: Plant functional groups and soil N: Plant density effects

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INTRODUCTION

The relatively recent shifts in community composition and structure of native sagebrush steppe ecosystems have important implications for regional biodiversity. Increasing cheatgrass (*Bromus tectorum* L.) dominance has negatively affected native plant and animal populations in the Great Basin (Mack 1981; Wiens and Rotenberry 1981; MacCracken and Hansen 1982; Wiens and Rotenberry 1985; Young and Allen 1997; Johnson and Braun 1999; Vander Haegen et al. 2000; West and Young 2000). The replacement of native shrublands by cheatgrass significantly affects native plant species regeneration, seed production, dispersal, and even the patterns of seedling establishment.

As cheatgrass dominance in Great Basin ecosystems increases, it is important to understand the specific traits and mechanisms favoring its success and those limiting the occurrence and abundance of native species. Competition intensity can affect the outcome of the interactions between natives and invaders and determine invader's success (Daehler 2003). Davis et al. (2000) proposed that invasibility can be related to the amount of unused resources. Consequently, an increase in the availability of limiting resources will decrease the resistance of a community to invasion and favor the invader's establishment. In contrast, factors that reduce resource availability may decrease the susceptibility of the community to invasion. Studies in the Great Basin suggest that resource sequestration by the native vegetation restricts cheatgrass establishment (Booth et al. 2003, Beckstead and Augspurger 2004). However, cheatgrass benefits when resource availability increases as a result of disturbances that reduce consumption by native perennial vegetation (Melgoza and Nowak 1991, Chambers et al. 2007).

Nitrogen availability influences the dominance of disturbed range ecosystems by annual exotics (McLendon and Redente 1991). When resources are available, species like cheatgrass with high growth rates can rapidly spread by allocating resources to aerial biomass (Mclendon and Redente 1991; Tilman and Wedin 1991; Blicker et al. 2002) thus depleting resources for the slow growing perennials. This demand for nutrient acquisition might represent a disadvantage for annual exotics when nutrient supply is low (Young et al. 1998; Paschke et al. 2000; Herron et al. 2001; Ewing 2002). Slower growing perennial species are often able to divert resources to maintain absorptive surfaces under nutrient poor conditions (Campbell and Grime 1989).

Numerous studies have focused on the effects of low nutrient availability on exotic annuals (Campbell and Grime 1989; Young et al. 1998; Lowe et al. 2002; Monaco et al. 2003), but there is limited information on the performance of native sagebrush steppe species under natural conditions when nitrogen supply is reduced. Understanding the mechanisms driving native species recruitment is a critical issue for restoring biodiversity in degraded sagebrush ecosystems.

This experiment was carried out in a typical post-fire plant community dominated by cheatgrass, where nitrogen supply was manipulated using sucrose addition to promote N immobilization in the soil microbial biomass. We asked the following questions: (1) Is low nitrogen availability (caused by sucrose addition) more detrimental to the annual exotic cheatgrass than to the seeded perennial species?; (2) Does seeding density have a direct effect on the establishment of cheatgrass and perennial species?; (3) Does increasing density of cheatgrass have a negative effect on target perennials establishment?; and (4) Does a reduction in cheatgrass competitive ability due to sucrose addition promote perennial species establishment (*i.e.*, the relaxation of competition should provide a window of opportunity for perennials species establishment).

MATERIALS AND METHODS

Study Area

The study area is located in Eden Valley near Winnemucca, Humboldt County, Nevada (41°12′N, 117°23′W, elevation ~1524 m). The average annual precipitation is 300-330 mm, mostly occurring in the fall and winter. Historically, the vegetation at the site would have been representative of Wyoming big sagebrush habitat (*Artemisia tridentata* ssp. *wyomingensis*). Sagebrush habitat conversion to annual grassland occurred after the summer of 1999 when the area was burned by an extensive wildfire. Currently, the vegetation is dominated by *Bromus tectorum* and other exotic annuals such as *Sisymbrium altissimum*. Common herbivores of the community include ungulates (pronghorn antelope), small mammals (jackrabbit, cottontail rabbit, grasshoppers and Mormon crickets, among others (M. Mazzola, personal observation). A complete soil description is provided in Chapter 4.

Experimental Design

The study area (~ 25 ha) was grazed by livestock until the fall of 2002 when it was fenced to exclude cattle. Other herbivores were not excluded. The experiment was established as a randomized split-plot design with three replicates seeded in fall of 2003 and 2004 (layout for one year of the experiment is shown in **Fig. 7.1**). Two levels of carbon addition (none or 150g C m^{-2}) were applied as the whole-plot factor and used to examine the effect of reduced available N on cheatgrass and native species establishment. During each fall seeding, three replicates were treated with sucrose and three were left untreated (= control).

To determine the effects of seeding density, individual plots (1.5 x 2.5 m separated by 2.0 m buffer strips) within each replicate randomly received different seed mixtures resulting from the factorial combination of different cheatgrass seeding densities (BTSD) and perennial target species (TSD) as follows: **(A) Native perennial species-cheatgrass***:* To test the performance of perennial target species, we used different seed mixtures arranged in a factorial combination of a native target species mixture seeded at 4 densities (TSD = 0, 150, 300, and 600 viable seeds m^{-2}) and *B. tectorum* seeded at 5 densities (BTSD = 0, 150, 300, 600, and 1200 viable seeds m^{-2}). The species used in the seed mixture were: *Artemisia tridentata* ssp. *wyomingensis* (sagebrush, a native perennial shrub), *Poa secunda* (bluegrass bunchgrass, a native perennial grass), *Elymus multisetus* (squirreltail, a native perennial grass), *Pseudoroegneria spicata* (bluebunch wheatgrass, a native perennial grass), *Achillea millefolium* (yarrow, a native perennial forb) and *Sphaeralcea coccinea* (scarlet globe mallow, a native perennial forb); or **(B) Vavilov-cheatgrass:** To test the performance of Vavilov Siberian wheatgrass, a subset of plots was seeded with a combination of Vavilov Siberian wheatgrass (*Agropyron fragile,* an introduced perennial grass) at 2 seeding densities (TSD = 0 and 300 viable seeds m^{-2}) and cheatgrass at 5 densities (BTSD = 0, 150, 300, 600, and 1200 viable seeds m^{-2}). See Chapter 6-Materials and Methods for a detailed description of experimental design and treatments.

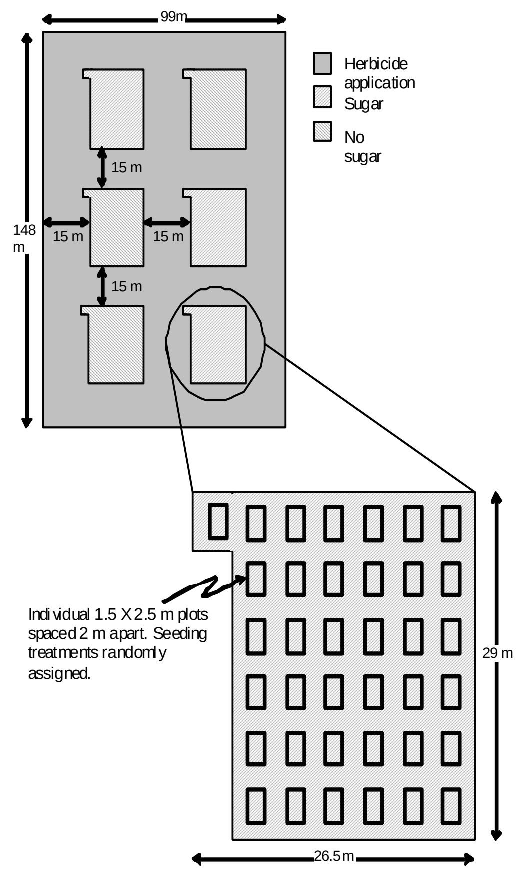

Fig. 7.1. Plot configuration for one year of study, showing experimental layout of 6 replicates in a randomized block design at top and details of plots within 1 replicate at bottom (also shown some additional plots not included in this experiment).

Seedbank Sampling

To evaluate the pre-existing seed bank, we sampled

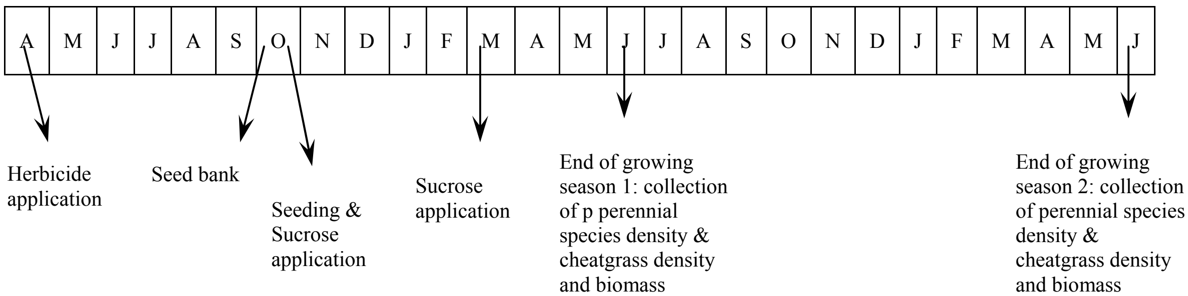

Fig. 7.2. Schematic timeline of the experiment showing treatment applications and data collection.

the Experiment 2 areas after the last herbicide application and before the fall seeding for both the 2003 and 2004 replicates of the experiment.

Plant Density, Biomass and Reproductive Output

In June 2004, 2005, and 2006, we sampled density of target species and cheatgrass in every individual plot. At the same time, we collected up to 15 cheatgrass plants per plot and processed them to assess vegetative biomass, seed biomass and seed output. A complete description of sampling procedures and measurements can be found in Chapter 6: Materials and Methods. A schematic timeline of the experiment is shown in **Fig. 7.2**.

Data Analysis

Plant responses were analyzed as a blocked split-split plot design using a mixed model analysis of variance (SAS PROC MIXED). Seeding year was a blocking factor, a random effect to account for annual variation and seeding location with sucrose as the whole plot factor, and the factorial combination of target species and cheatgrass seeding densities as the split factor within seed year. Growing season was the second split and a repeated measure (to account for temporal correlation). For the purpose of this analysis, we consider the harvest date (June) as the end of each growing season.

The data presented in this report correspond to the density and biomass measurements conducted at the end of the first and second growing seasons after seeding and first sugar application. PROC TRANSREG (SAS 2001) was used to find the most appropriate transformation for each variable. Perennial target native species density at harvest was transformed using square root (x + 3/8) to meet normality. Cheatgrass density, biomass and seed output per plant and cheatgrass density and biomass m^{-2} and were transformed using *ln* (x + 0.0001) to meet normality whereas cheatgrass seed output m^{-2} was transformed using ($x^{0.25}$-1/0.25).

Due to the large variation in the data collected during the first growing season and the second growing season in 'native perennial species-cheatgrass' plots, the effects of sugar and seeding densities on cheatgrass variables were analyzed separately by growing season using the same mixed-effects model. Exploratory data analysis was conducted utilizing the SAS ALLMIXED macro (Fernandez 2006). For significant factors and interactions, least squares means were compared using the Tukey-Kramer test at the 0.05 significance level. Untransformed means (±SE) are presented in all tables and figures.

RESULTS

Seedbank

The pre-seeding composition of the seedbank at the study site is shown in Chapter 6. The mean number of seeds observed was 1228 seeds m^{-2} with annual species comprising 96.5% of the seedbank (Chapter 6). The only three native perennial species recorded were *Artemisia tridentata*, *Poa secunda* and *Lomatium nevadense*, which averaged between 2 and less than 1 seed m^{-2}. The almost complete absence of native perennials in the seedbank was not surprising given that few perennial sagebrush steppe species have long-lived seeds and that the conversion of sagebrush steppe grasslands to cheatgrass-dominated systems can cause a decline in the density of native perennial species seeds over time (Humphrey and Schupp 2001).

The seedbank on the soil surface contained 12 species with an average of 639 seeds m^{-2}. The introduced annuals *Draba verna* and *Bromus tectorum* accounted for ~80% of this portion of the seedbank. The seed content at the 0-5cm depth averaged 590 seeds m^{-2} and 18 species were recorded. This depth was dominated by *D. verna* (75%), followed by *Sisymbrium altissimum* (9.1%) and *B. tectorum* (8.6%). In contrast with the soil surface, lower densities of B. tectorum were found in the 0-5 cm depth. The introduced annual *Erodium cicutarium* and the natives *Vulpia octoflora* and *Phlox gracilis* also were abundant at the site.

Overall, exotic forbs and grasses almost completely dominated the seedbank (~87%) with the native species a minor component (9.7%). The seedbank composition reflected the aboveground composition of the plant community during the study period when an almost complete dominance of annual species was observed (M. Mazzola, personal observation).

Soil Nutrients

Nitrate levels in the soils were higher immediately after the herbicide application, likely due to reduced plant uptake. Sucrose application significantly reduced NO_3^- availability at the 0-15 cm depth during the first year of the study, but the effect weakened with time and was not significant by the second growing season (see **Fig. 4.3**). Similarly to NO_3^-, available ortho-P was higher during the first growing season. However, unlike NO_3^-, ortho-P availability increased over time. More detailed results about sucrose effects on soil nutrients are given in Chapter 4.

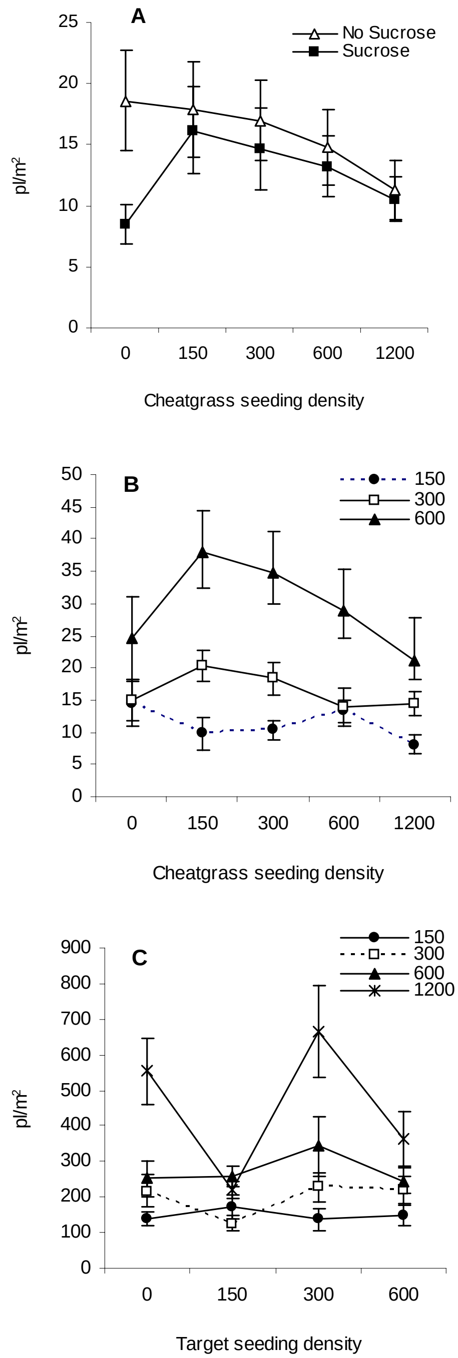

Fig. 7.3. (A) Number of native perennial plants (plants m five cheatgrass seeding densities (0, 150, 300, 600 and seeds m^2) and two sucrose treatments at the end of th growing season; (B) Number of native perennial plants (m^2) for the five cheatgrass seeding densities at each le target native species seeding densities (150, 300, and 600 m^2) at the end of the first growing season; and (C) Num cheatgrass plants (plants m^2) for the four native species se densities (0, 150, 300, and 600 seeds m^2) for each le cheatgrass seeding densities at the end of the first gr season. Values shown represent mean ±SE.

Native Species-Cheatgrass Plots

Native species

The temporary reduction of available N did not have a significant effect on native seedling establishment ($F_{1,12}$ =

3.58, p = 0.0828). There was a significant sugar*target native seeding density interaction ($F_{2,168}$ = 3.15, p = 0.0452; **Fig. 7.3A**) in which natives had higher numbers on sucrose treated plots in the absence of cheatgrass. The interaction sugar*cheatgrass seeding density was also significant ($F_{4,168}$ = 2.64, p = 0.0355).

Increasing seeding density of the target native species had a strong positive effect on seedling density ($F_{2,168}$ = 65.69, p <0.0001) resulting in increased overall seedling numbers by the end of the first growing season (**Fig. 7.4**). There were strong growing season effects, with the first growing season resulting in much higher plant numbers that the second. None of the native species emerged in plots that were not seeded indicating no contribution from the seedbank.

The seeding treatments had different effects on individual species (**Table 7.1**). *Artemisia tridentata, Achillea millefolium, Poa secunda* and *Pseudoroegneria spicata* all showed significantly higher seedling establishment as seeding density increased. *Elymus multisetus* had generally low establishment. *Sphaeralcea coccinea* seedlings were not observed during the study, and this species was omitted from the analyses. It is likely that the innate dormancy of *S. coccinea* seeds was not broken by the environmental conditions during the study period.

There was a highly significant effect of growing season on native species density ($F_{1,\ 180}$ = 1179.38, p <0.0001; **Fig. 7.4**). The highest number of seedlings was observed at the end of the first growing season (June) after the prior year's seeding. Seedling mortality was high, and few seedlings survived in any treatments to the end of the second growing season. At that point, 10.9 and 16 individuals m^{-2} senesced, on average, in the low and intermediate native seeding rates. Meanwhile, mortality reached 27.7 individuals m^{-2} on the high density treatment.. From the lowest to the highest seeding treatments the overall survival rates were 3, 2 and 6%. Given that native plant density was similar in all seeding treatments by the second season of the study (**Fig. 7.4**), the significant interaction native seeding density*season ($F_{2,\ 180}$ = 24.10, p <0.0001) could be attributed to the larger seedling mortality observed in the high seeding treatments.

During the first year of establishment, *Artemisia tridentata*, had the highest density, followed by *Achillea millefolium*, *Poa secunda*, *Pseudoroegneria spicata*, and finally *Elymus multisetus*. Despite of the effect of seeding density, by the end of the second year, , all species, with the exception of *P. spicata,* had on average less than one individual surviving (**Table 7.1**).

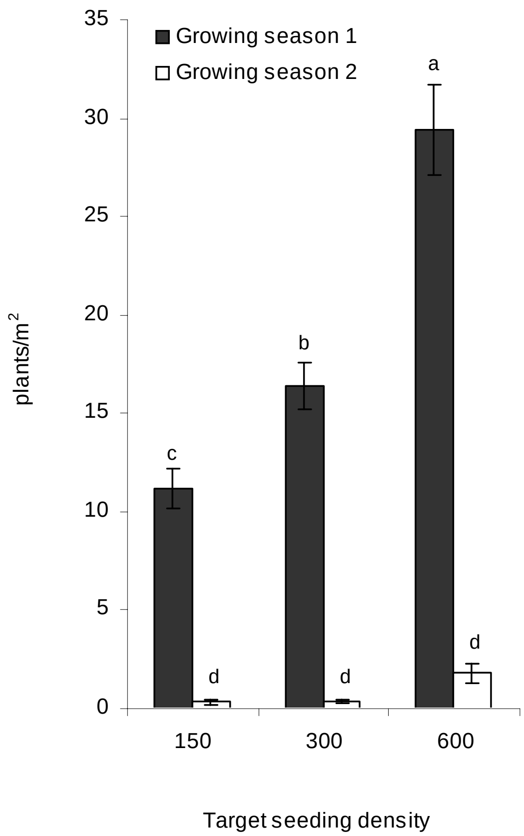

Fig. 7.4. Mean (±SE) total number of native perennial species individuals per square meter for each target native species seeding density (TSD = 150, 300 and 600 seeds m^2) at the end of the first (■) and second growing season (□) after seeding. Different lowercase letters indicate significant differences (P_{Tukey}<0.05).

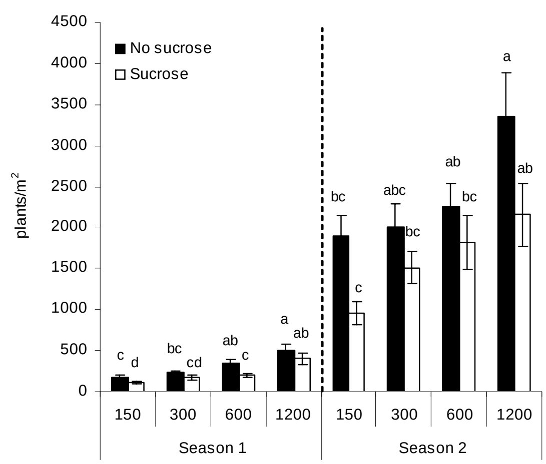

Fig. 7.5. Mean (±SE) cheatgrass density in no sucrose (■) and sucrose (□) plots for four cheatgrass seeding densities (150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within growing season (P_{Tukey}<0.05).

Table 7.1. Mean (± SE) number of plants per square meter for the three target native seeding density treatments (TSD = 150, 300 and 600 seeds m^2) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within rows (P_{Tukey}<0.05).

Species	Growing season 1						Growing season 2					
	TSD = 150		TSD = 300		TSD = 600		TSD = 150		TSD = 300		TSD = 600	
A. tridentata	2.3 (0.4)	c	3.6 (0.5)	b	7 (0.9)	a	0	d	0	d	0	d
A. millefolium	2.7 (0.4)	b	3.9 (0.5)	ab	6.5 (1.2)	b	0.1 (0.03)	c	0.1 (0.04)	c	0.2 (0.1)	c
P. secunda	2.2 (0.3)	b	2.9 (0.4)	b	5.1 (0.6)	a	0	c	0	c	0.9 (0.4)	c
P. spicata	0	b	2.6 (0.4)	b	6.4 (1.1)	a	2.5 (0.4)	c	0	c	0.2 (0.1)	c
E. multisetus	0.9 (0.3)	bc	1.8 (1.3)	a	1.3 (0.3)	ab	0.1 (0.1)	d	0.2 (0.1)	cd	0.4 (0.1)	bcd

Horizontal comparisons, different lowercase letters indicate significant differences (Tukey-Kramer, P<0.05).

Cheatgrass seeding density influenced the number of native species seedlings that established ($F_{4, 168}$ = 3.34, p = 0.0116; **Fig. 7.3B**). The effect of cheatgrass seeding density depended on target native seeding density ($F_{8, 168}$ = 2.13, p = 0.0352). When analyzing the response of the native species to the seeding treatment during the first year of establishment we should take into account the effect of the interaction between native seeding rate and cheatgrass seeding rate as well as the actual number of cheatgrass plants recruited in each treatment (**Figs. 7.3B and 7.3C**). During the first growing season, at a native seeding rate of 600, a higher number of perennial seedlings was observed in the BTSD=150 treatment compared to the highest cheatgrass seeding rate (BTSD=1200). The addition of only 150 cheatgrass seeds m^{-2} resulted in average cheatgrass densities ranging between 148 and 164 plants m^{-2} across all native seeding treatments. At this low cheatgrass density, we observed the strongest effect of native seeding density on establishment. The addition of seeds to those plots without cheatgrass did not follow this pattern and regardless of the number of seeds added, all treatments recruited similar number of seedlings.

It appears that the highest native seeding rate was more effective when the actual cheatgrass densities were less than ~300 plants m^{-2} and less effective when cheatgrass densities were above 300 plants m^{-2} (363 ±76) plants m^{-2}. When native seeding densities were lower (150 and 300), seedling establishment was similar regardless of cheatgrass seeding density or the number of cheatgrass plants present in the plot (whose number ranged anywhere from 0 to more than 660 m^{-2}). Although not significant, a slightly higher number of seedlings established with cheatgrass seeding density =150 treatment that had an average of 136 (±33) cheatgrass plants m^{-2}.

Cheatgrass density

The reduction in plant available N after sucrose addition significantly reduced cheatgrass density during the first growing season after seeding ($F_{1, 2}$ = 20.38, p = 0.0458). There was a 29 % reduction in the number of *B. tectorum* plants establishing per square meter (**Table 7.2**). Cheatgrass seeding density had a significant effect on cheatgrass establishment ($F_{3,178}$ = 32.93, p <0.0001). In general, increasing seeding density increased plant density (**Fig. 7.5**) regardless of sugar treatment (Sugar*cheatgrass seeding density: $F_{3,178}$ = 0.78, p = 0.5092). The highest cheatgrass density (BTSD=1200 seeds m^{-2}) produced more cheatgrass plants than the low seeding density treatment (BTSD=150 seeds m^{-2}) (P_{Tukey} <0.05) whereas, the BTSD=300 and BTSD=600 seeds m^{-2} rates resulted in intermediate density values. There was an interaction between cheatgrass and native species seeding densities ($F_{9, 178}$ = 2.51, p =0.0099). All cheatgrass seeding densities yielded similar number of plants within each native species seeding treatment, except in the combination of BTSD=1200 seeds m^{-2} and TSD=150 seeds m^{-2} which have a significantly lower value than the BTSD=1200 seeds m^{-2} and TSD=300 seeds m^{-2} treatment (P_{Tukey}<0.05) (**Fig. 7.3C**).

By the end of the following growing season, cheatgrass density had markedly increased in all plots compared to the previous year (**Fig. 7.5**). There was still a significant effect of the sucrose addition ($F_{1,10}$ = 7.23, p =0.0227), and an overall reduction of 32% was still observed in cheatgrass density (**Table 7.2**). Despite the overall pattern of higher densities in the no sucrose plots compared to the treated plots at each cheatgrass seeding densities (**Fig. 7.5**), these differences were not significant at the P=0.05 level. The lack of significant differences may be attributed to the large variability in the data. The cheatgrass seeding rate was still highly significant ($F_{3,180}$ = 7.95, p <0.0001) and less numbers of plants were recorded in the BTSD=150 and 300 seeding treatments compared to the BTSD=1200 seeds m^{-2} rate (P_{Tukey} <0.05).

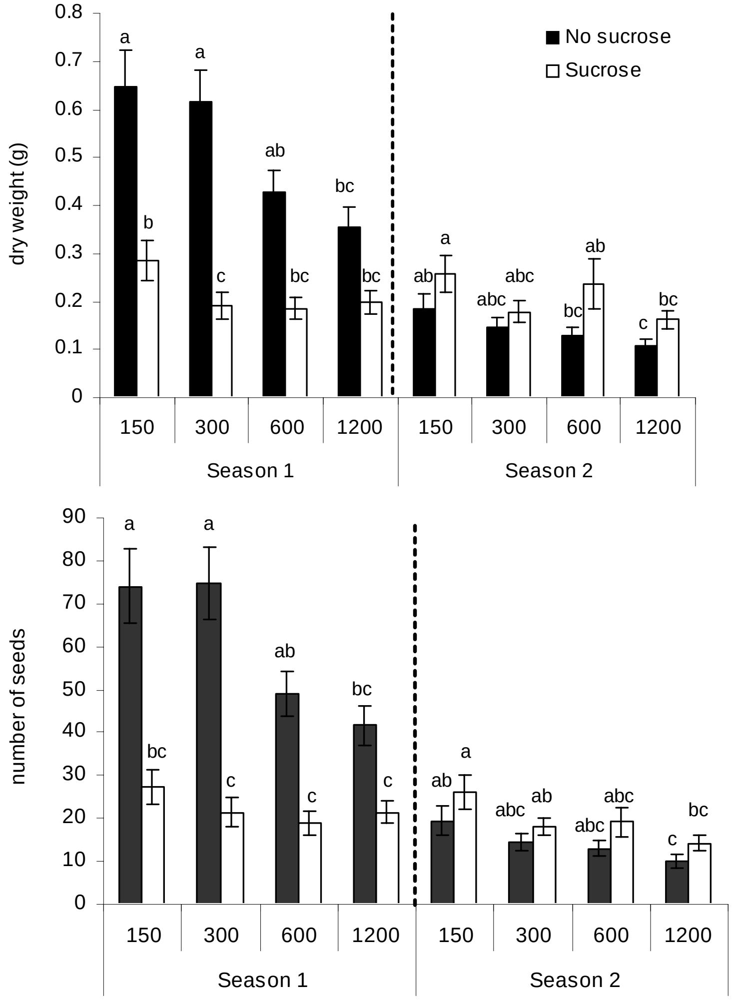

Fig. 7.6. Mean (±SE) cheatgrass biomass (above) and seed production (below) per plant in no sucrose (■) and sucrose (□) plots for four cheatgrass seeding densities (150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within growing season (P_{Tukey}<0.05).

Cheatgrass biomass and seed production per plant

During the first growing season, sucrose application had a significant negative effect on the total aboveground biomass produced per individual cheatgrass plant ($F_{1,4}$ = 13.04, p =0.0225; **Fig. 7.6**). There was an overall reduction of 58% in the plants growing in the sucrose plots compared to those growing in the control plots (**Table 7.2**). Sucrose also affected the number of filled seeds per plant ($F_{1,4}$ = 17.114, p = 0.0144; **Fig. 7.6**) causing an overall reduction of 63%.

Cheatgrass seeding density also had a significant effect on individual aboveground biomass ($F_{3,178}$ = 7.56, p <0.0001) and seed production ($F_{3,178}$ = 5.48, p = 0.0013) (**Fig. 7.7**). Furthermore, sugar and cheatgrass seeding treatment interacted significantly with biomass ($F_{3,178}$ = 5.41, p = 0.0014) and seeds per plant ($F_{3,178}$ = 3.76, p = 0.0120). Aboveground biomass and seed output per plant data are shown in **Fig. 7.5**. In the no sucrose plots, a general pattern of decreasing size and seed output per plant was observed with higher seeding densities. Plants in the lower density seeding treatments (BTSD=150 and 300 seeds m^{-2}) were significantly larger (P_{Tukey} <0.05) and produced more seeds than those in the higher seeding rate (BTSD=1200 seeds m^{-2}), whereas the BTSD=600 seeds m^{-2} treatment showed intermediate values.

On the sucrose treated plots, only plant size was affected. Plants tended to be produce more biomass in the lowest cheatgrass seeding treatment (BTSD=150 seeds m^{-2}) and less biomass when seeded at 300 seeds m^{-2} (P_{Tukey} <0.05). The two higher cheatgrass seeding rates had intermediate values. Meanwhile, the average number of seeds per individual was similar regardless of cheatgrass seeding density.

When comparisons were made at each cheatgrass seeding level, plants growing at the BTSD=150 and 300 seeds m^{-2} levels showed significant differences between sucrose and no sucrose treatments (P_{Tukey} <0.05). No differences in plant biomass were observed between sucrose treatments when seeding rates were higher. In the case of individual seed production, with the exception of the BTSD=1200 level, all treatments showed significant reductions in seed output due to sucrose (P_{Tukey}<0.05).

By the following year, the effects of sugar ($F_{1,10}$ = 6.11, p =0.0330) and cheatgrass seeding density ($F_{3,180}$ = 9.37, p <0.0001) on individual aboveground biomass were still significant but plants were, in general, smaller across all treatments (**Fig. 7.5**). As regards to seed output, sucrose was no longer significant ($F_{1,10}$ = 3.97, p =0.0743) while cheatgrass seeding rate ($F_{3,180}$ = 8.66, p <0.0001) still had a strong effect by the end of the second growing season. Similarly to biomass, seed production was, in general, lower across all treatments (**Fig. 7.5**). Plants grew larger and produced more seeds in the lowest seeding treatment and grew smaller producing less seeds at the highest seeding rate (P_{Tukey} <0.05). Intermediate cheatgrass seeding rates yielded intermediate values (**Fig. 7.6**). No differences in biomass or seeds were observed between sucrose and control plants when both variables were analyzed at each BTSD level.

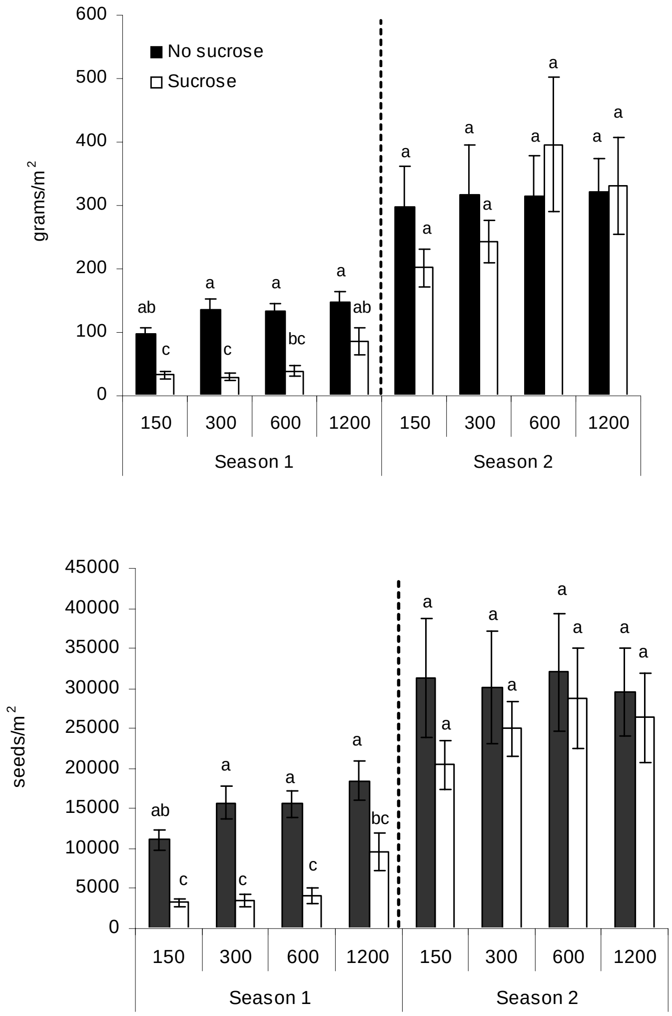

Fig. 7.7. Mean (±SE) cheatgrass aboveground biomass/m^2 (above) and seed output/m^2 (below) in no sucrose (■) and sucrose (□) plots for four cheatgrass seeding densities (150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within growing season (P_{Tukey}<0.05).

Cheatgrass biomass and seed production per square meter

When individual plant biomass and seed output at the end of the first growing season were scaled to the square meter, sucrose application had a significant negative effect on both variables (aboveground biomass: $F_{1,4}$ = 13.85, p = 0.0205; seed output: $F_{1,4}$ = 16.59, p = 0.0153). Overall, the treated plots produced 63% less aerial biomass and 66% less seeds per square meter than the control plots (**Table 7.2**). Cheatgrass seeding density also had a significant effect on biomass m^{-2} ($F_{3,178}$ = 7.89, p < 0.0001) and number of seeds m^{-2} ($F_{3,178}$ = 9.14, p < 0.0001) in the first year of study. Both variables showed a similar pattern of larger values in the high seeding density treatment (**Fig. 7.7**). There was a significant effect of the interaction between sugar and cheatgrass seeding rate on biomass m^{-2} ($F_{3,178}$ = 3.46, p = 0.0176). The p–value for this interaction was just above the 0.05 level on the number of seeds m^{-2} ($F_{3,178}$ = 2.37, p = 0.0718). In both cases, the high density treatment (BTSD=1200 seeds m^{-2}) did not show any significant

Table 7.2. Mean (±SE) cheatgrass density, aboveground biomass/plant, seed output/plant, aboveground biomass m^{-2}, and seed output m^{-2} in each sucrose treatment at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences in the horizontal comparisons (P_{Tukey}<0.05).

Variable	Unit	Growing season 1		Growing season 2	
		No Sucrose	Sucrose	No Sucrose	Sucrose
Density	plants m^{-2}	315 (26) c	223 (22) d	2379 (184) a	1614 (146) b
Aboveground biomass	grams $plant^{-1}$	0.512 (0.031) a	0.214 (0.015) b	0.141 (0.011) c	0.209 (0.018) b
Seed output	seeds $plant^{-1}$	59.9 (3.8) a	22.2 (1.6) b	14.2 (1.2) c	19.3 (1.5) b
Aboveground biomass	grams m^{-2}	127.7 (7.7) b	47.2 (6.5) c	312.1 (32.4) a	292.6 (34) a
Seed output	seeds m^{-2}	15211 (993) b	5167 (728) c	30763 (3382) a	25131 (2371) a

Horizontal comparisons, different lowercase letters indicate significant differences (Tukey-Kramer, P<0.05).

differences between sucrose and no sucrose plots; whereas sucrose plots yielded less biomass and seeds per square meter at each one of the remaining seeding rates (P_{Tukey} <0.05).

At the end of the second growing season, both cheatgrass biomass m^{-2} and seed output m^{-2} were considerably higher in all treatments in comparison with the previous year (**Fig. 7.7**). There was at least a 2-fold increase in both variables in the control plots, whereas the sugared plots had about a 5- to 6-fold increase in biomass m^{-2} and number of seeds m^{-2} respectively. These increases resulted in all plots yielding similar aerial biomass and number of seeds per square meter regardless of sugar and/or seeding treatment.

Vavilov-Cheatgrass Plots

Vavilov Siberian wheatgrass

The significant reduction of soil N availability during the first growing season had no effect ($F_{1,2}$ = 0.04, P = 0.8682) on overall *Agropyron* seedling numbers and as a result, similar density values were recorded in sugared and control plots. However, seedling numbers of Vavilov wheatgrass were significantly affected by cheatgrass seeding density ($F_{4,48}$ = 3.22, p = 0.0202) and growing season ($F_{1,60}$ = 37.73, p < 0.0001). The interaction between these two factors was also significant ($F_{1,60}$ = 5.03, p = 0.0286).

As shown in **Fig. 7.8**, more *Agropyron* plants established in plots where cheatgrass was absent (BTSD=0

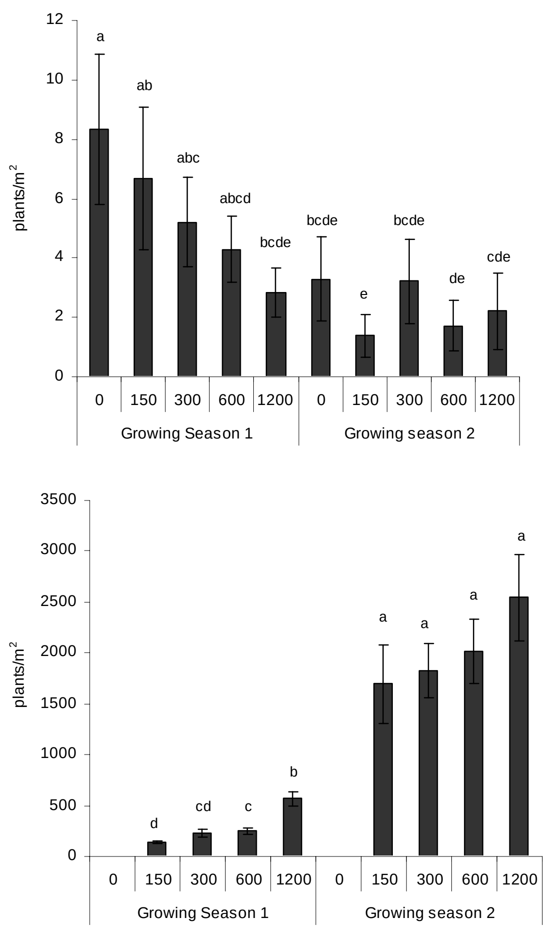

Fig. 7.8. Mean (±SE) number of Vavilov wheatgrass (above) and cheatgrass (below) plants (plants m^{-2}) for five cheatgrass seeding densities (0, 150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences (P_{Tukey}<0.05).

seeds m^{-2}) during the first growing season while the lowest recruitment was observed in plots where cheatgrass was seeded at the highest density (BTSD=1200 seeds m^{-2}). Intermediate density values were observed at intermediate seeding rates. Although establishment was slightly higher when Vavilov was not competing with cheatgrass, the number of seedlings per square meter was not significantly higher from the number of seedlings observed when cheatgrass was seeded at densities ≤ 600 seeds m^{-2} which yielded no less than 300 cheatgrass plants m^{-2}. Seedling numbers were lowest when cheatgrass was seeded at the highest rate (1200 seeds m^{-2}) and reached a density of 567 (±69) plants m^{-2}.

By the end of the following year survivorship was about 40, 21, 62, 40 and 78% in BTSD=0, 150, 300, 600 and 1200, respectively (**Fig. 7.8**). As a result, the number of surviving Vavilov plants was similar among seeding treatments, and the overall density was similar to that recorded in the previous year in the high cheatgrass density plots.

Cheatgrass density

Despite the strong sucrose effects on soil N availability immediately after the sucrose application (see Chapter 4), the effects of sucrose on cheatgrass were marginally significant ($F_{1,\ 10}$ = 5.04, p = 0.0487). There was an overall reduction in cheatgrass density of about 25 % in the treated plots in comparison with the controls (**Table 7.3**). Cheatgrass was not affected by the presence of *Agropyron* plants ($F_{1,\ 180}$ = 1.65, p = 0.2006).

There were a significant effect of cheatgrass seeding density treatment ($F_{3,180}$ = 20.19, p < 0.0001) and growing season ($F_{1,180}$ = 469.08, p < 0.0001). The interaction between these two factors was also significant ($F_{3,180}$ = 5.37, p = 0.0015). During the first growing season, cheatgrass density increased with increasing seeding density. As a result, the highest values were recorded at the BTSD=1200 level and the lowest in the BTSD=150 level (P_{Tukey} <0.05); intermediate levels have intermediate values and did not differ from each other (**Fig. 7.8**). The number of cheatgrass plants per square meter was much higher in the second growing season than in the preceding one (P_{Tukey} <0.05), and there were no significant differences among cheatgrass seeding treatments (**Fig. 7.8**).

Total aboveground biomass and seeds produced per individual cheatgrass plant were negatively affected by the sucrose application (biomass: $F_{1,10}$ = 8.33, p = 0.0162; seed output: $F_{1,10}$ = 5.40, p = 0.0425). In the first growing season, there was an overall reduction in both variables of about 63% in the sucrose plots compared to the control plots (**Table 7.3**).

Table 7.3. Mean (±SE) cheatgrass density, aboveground biomass plant^{-1}, seed output plant^{-1}, aboveground biomass m^{-2}, and seed output m^{-2} by sucrose treatment at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within rows (P_{Tukey}<0.05).

Variable	Unit	Growing season 1		Growing season 2	
		No Sucrose	Sucrose	No Sucrose	Sucrose
Density	plants m^{-2}	316 (34) b	239 (36) b	2422 (272) a	1538 (175) a
Aboveground biomass	grams plant^{-1}	0.601 (0.047) a	0.218 (0.018) b	0.140 (0.013) c	0.227 (0.032) b
Seed output	seeds plant^{-1}	66.7 (5.9) a	23.0 (2.2) b	12.7 (1.3) c	20.3 (2.3) b
Aboveground biomass	grams m^{-2}	158.7 (18.8) b	52.7 (11.3) c	347.3 (53.4) a	302.8 (50.3) ab
Seed output	seeds m^{-2}	17627 (2149) a	5740 (1165) b	29722 (4474) a	25166 (2964) a

Horizontal comparisons, different lowercase letters indicate significant differences (Tukey, P<0.05).

The biomass responses significantly changed over time (growing season: $F_{1,180}$ = 95.14, p < 0.0001; sugar*growing season: $F_{1,180}$ = 85.47, p < 0.0001). By the next year, the control plants showed a significant decrease in aerial biomass (P_{Tukey} <0.05) whereas the sugared plants yielded similar biomass in both years (**Fig. 7.9**). Seed production per plant showed a similar pattern (growing season: $F_{1,180}$ = 86.06, p < 0.0001), and there was a sugar*growing season interaction ($F_{1,180}$ = 69.99, p < 0.0001) (**Fig. 7.9**).

Cheatgrass seeding density also had a significant effect on individual aboveground biomass ($F_{3,180}$ = 4.14, p = 0.0072) and its effects are more clear when the interaction of sugar*cheatgrass seeding density*growing season ($F_{3,180}$ = 2.56, p = 0.0568) is analyzed. In the control plots, the effect of sugar becomes less evident during the first growing season with increasing cheatgrass seeding densities until it becomes not significant in the highest cheatgrass seeding density plots (**Fig. 7.9**). However, plants in sugared plots had similar weights. By the next growing season, the control plants were similar across all BTSD levels but were significantly smaller than in the preceding year (P_{Tukey}<0.05). In contrast, the dry weights of sugared plants remained similar to each other and to those in the previous growing season.

The effect of cheatgrass seeding density on the seed output of individual plants was not significant ($F_{3,180}$ = 2.35, p = 0.0741). Although it appears that seed production was slightly higher with lower seeding densities, no significant differences were observed across cheatgrass seeding treatments at the 0.05 level. In general, seed production plant^{-1} followed a similar pattern to biomass plant^{-1}. Control plants tended to produce more seeds during the first growing season after sucrose application, whereas seed production was not affected in the second growing season on the sugared plots) (**Table 7.3**, **Fig. 7.9**).

Cheatgrass aboveground biomass and seed production per square meter

Both the production of cheatgrass seeds and aerial biomass per square meter were significantly (seeds m^{-2}: $F_{1,10}$ = 13.65, p = 0.0041) or marginally (biomass m^{-2}: $F_{1,2}$ = 11.47, p = 0.0772) affected by the application of sucrose, which caused an initial reduction of ~67% in both variables when comparisons were made between control and sucrose plots. The responses varied with growing season (seeds m^{-2}: $F_{1,180}$ = 62.80, p <0.0001; biomass m^{-2}: $F_{1,180}$ = 116.64, p <0.0001) (**Table 7.3**) and also depended on the sugar*growing season interaction (seeds m^{-2}: $F_{1,180}$ = 26.63, p <0.0001; biomass m^{-2}: $F_{1,180}$ = 42.90, p <0.0001). Cheatgrass seeding density also had a significant effect on the amount of biomass ($F_{3,178}$ = 5.23, p = 0.0017) and the number of seeds m^{-2} ($F_{3,180}$ = 3.98, p = 0.0089) at the square meter level. The interaction between cheatgrass seeding density and growing season was marginally significant in the case of biomass (biomass m^{-2}: $F_{3,,180}$ = 2.32; p = 0.0.769) but was not significant for the number of seeds m^{-2} ($F_{3,,180}$ = 1.62, p = 0.1874).

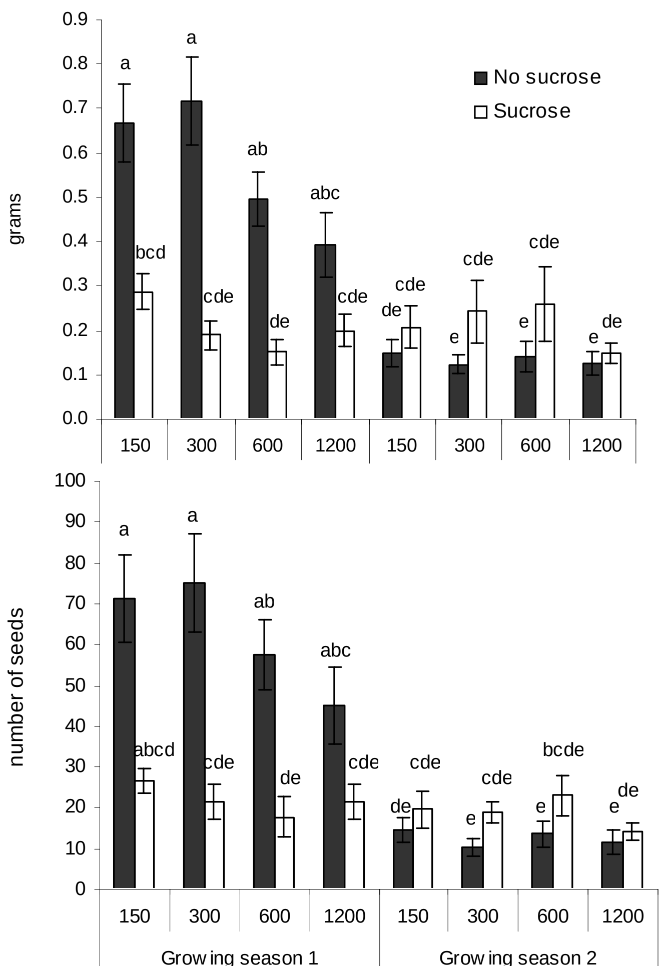

Fig. 7.9. Mean (±SE) cheatgrass aboveground biomass m^{-2} (above) and seed production m^{-2} (below) in sucrose and no sucrose treatments at each level of cheatgrass seeding density (150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences (P_{Tukey}<0.05).

Table 7.4. Mean (±SE) cheatgrass aboveground biomass m^{-2} and seed output m^{-2} in sucrose and no sucrose treatments at each level of cheatgrass seeding density (150, 300, 600 and 1200 seeds m^{-2}) at the end of the first and second growing season after seeding. Different lowercase letters indicate significant differences within column (P_{Tukey}<0.05).

Growing Season	Sucrose	Cheatgrass seeding density (seeds m^{-2})	Biomass (g m^{-2})			Seed output (seeds m^{-2})		
			Mean	SE		Mean	SE	
1	No sucrose	150	90.5	15.3	cde	10210	1751	ab
		300	214.0	41.5	abc	20979	4220	a
		600	138.8	24.2	abc	16201	3066	a
		1200	217.3	59.4	abc	25213	7019	a
	Sucrose	150	38.2	9.3	bdef	3837	1033	b
		300	27.2	6.6	f	3100	797	b
		600	28.8	6.7	ef	3511	1124	b
		1200	129.6	43.5	bd	13705	4316	ab
2	No sucrose	150	220.2	64.7	abc	20001	4580	a
		300	351.3	115.8	abc	30607	10451	a
		600	386.1	131.8	abc	34911	11893	a
		1200	373.3	102.0	ab	34809	10410	a
	Sucrose	150	245.1	57.0	abc	21123	4289	a
		300	299.7	92.8	ac	23452	4069	a
		600	441.6	192.7	abc	33246	11041	a
		1200	246.8	46.5	abc	22710	3970	a

Vertical comparisons among means, different lowercase letters indicate significant differences (Tukey-Kramer, P<0.05).

During the initial year of the study, no significant differences in biomass m^{-2} were observed in the control plots (**Table 7.4**). In the sucrose plots, the high seeding density treatment (BTSD=1200) yielded more biomass than the BTSD=300 and 600 treatments (P_{Tukey}<0.05) with BTSD=150 being intermediate. By the second year, aboveground biomass production substantially increased in comparison with the previous year (P_{Tukey}<0.05) and all treatments produced similar amounts.

During the first growing season, the number of seeds per square meter was significantly reduced by sucrose only in those plots where cheatgrass was seeded at 300 and 600 seeds m^{-2} (**Table 7.4**). By the following growing season, these plots had significantly higher seed production and seed numbers were similar to the other plots.

DISCUSSION

As expected, soil microbial biomass responded positively to the C addition, and N immobilization occurred in the top 15 cm of the soil profile. Resin capsule results showed that NO_3^- was less available for plant uptake in the sugared plots during this first growing season after the seeding. This effect was similar to the results found by other studies where short-term depletion of N occurred after the addition of a labile C source to the soil (Jonasson et al. 1996, Reever Morghan et al. 1999, Paschke et al. 2000). During the period when sucrose effects were significant, *B. tectorum* density, biomass and seed output were reduced below that of the control, providing evidence that low NO_3^- availability was a major constraint to the productivity of this annual species. These results are consistent with several other studies that have shown that low N supply negatively impacts invasive species (McLendon and Redente 1991; Young et al. 1998; Paschke et al. 2000; Herron et al. 2001; Ewing 2002, Monaco et al. 2003).

Cheatgrass was also affected by its own seed availability as increasing seeding rates resulted in higher densities. Although soil data for all the individual treatment combinations was not available, cheatgrass responses suggest increasing resource limitation towards higher cheatgrass seeding rates. The pattern observed in the control plots during the first growing season indicates that *B. tectorum* plants growing in low densities were not likely resource-limited because they were able to grow larger producing more individual photosynthetic biomass and seeds than those growing at the highest density. This response was not surprising as it has been observed that cheatgrass reduces its growth rate as a result of increasing intraspecific competition (Sheley and Larson 1997). Nitrogen immobilization after sucrose addition eliminated this trend resulting in similar plant size and seed output across all densities. In general, our results showed that when resources were available and (intraspecific) competition was lower, cheatgrass individuals maximized their growth and reproductive output. Thus, the reduction of plant size and seed output were likely the result of reduced resource supply due to N immobilization and/or greater competition intensity due to higher plant density. Cheatgrass response to the variation in resource supply was typical of fast-growing annual species. When resource availability is more or less optimal, fast-growing annuals increase their relative investment in photosynthetic tissue yielding more aboveground biomass. When grown under nutrient-poor conditions, these species typically slow down their relative growth rate thus producing less biomass and seeds (Lambers et al. 1998).

Competition between annual invaders and native perennials is influenced by the phenological stage of the species involved in the interaction. Generally, when perennials species are already established in the plant community, they are able to capture soil resources thus limiting the water and nutrient supply for annuals invaders (Duke and Caldwell 2001; Yoder and Caldwell 2002; Chambers et al. 2007). Nonetheless, perennial species are not competitively superior to cheatgrass at the seedling stage (Arredondo et al. 1998, Booth et al. 2003). Our results agree with these findings suggesting that the seedlings of the perennial target species which established primarily during the first growing season did not have any significant effect on cheatgrass performance.

The effects of the N gradient induced by sucrose and/or seeding density appeared to have dissipated by the second growing season. Although N supply appeared to be the main driver of cheatgrass responses during the first growing season after sucrose application, other factor(s) may also have contributed to the second year overall increase. Cheatgrass density increased in all treatments the following year after sucrose was applied. Because the reproductive output during the previous year was at least 5-fold higher than our initial highest seeding density, it is likely that the observed increase was primarily the consequence of the seed rain at the end of the first growing season. This resulted in higher propagule availability in all plots. The largest increase in density relative to the first year occurred in the control plots. As a result of the higher density, these plants were much smaller and produced fewer seeds whereas the weight and seed output of the sugared plants remained the same. At the square meter level, all control treatments considerably increased biomass and seed yield. Also, it appears that the sugared plots overcame the initial N immobilization effects and produced similar amounts of cheatgrass biomass and seeds than the controls by the end of the second growing season.

As mentioned before, intraspecific competition negatively impacts cheatgrass. The pronounced increase in density observed in our plots likely increased the effects of intraspecific competition thus resulting in much smaller plants producing fewer seeds. Despite the reduction in plant size and reproductive output, there was an overall increase in biomass and seed production per square meter. These observations lead to the question: how was cheatgrass able to recover so quickly and to such a large extent even when overall NO_3^- supply did not increase in the system?

Soil N is critical for invasive species establishment (McLendon and Redente 1991). In our study, it appears that during the second growing season, NO_3- availability was sufficient to support the observed high biomass and seed yields. While soil nitrate levels were not higher than the previous season, it is possible that the existing NO_3- levels at the beginning of the second growing season and the increasing overall P availability (Chapter 4) have combined to favor cheatgrass establishment and biomass and seed production at the square meter level. The fact that more plants were establishing per square meter could have resulted in a much larger volume of soil explored by cheatgrass roots, even when the individual plant size was small. Booth et al. (2003) showed that N acquisition by newly emerged cheatgrass is substantial despite minimal seedling biomass. In our case, increased root foraging activity in search of water and nutrients may have been responsible for the higher yields. It is also possible that other nutrients have built up in the soil due to reduced plant uptake in the previous two years (*i.e.*; first due to herbicide application and then due to lowered cheatgrass densities). Then, the increasing yields could be the result of a more intensive exploration of the soil profile by cheatgrass and/or to an unknown increase in resource(s) supply during the second year of the experiment.

It is also possible that litter accumulation and microenvironmental modification may have improved cheatgrass establishment. In our study, we removed the litter present in the plots prior to applying the sucrose and seeding treatments. Although we applied a stabilizing net, there was no cheatgrass litter on the soil surface during the first growing season. The biomass yielded during the first growing season accumulated on the soil surface and was largely present throughout the following growing season. Studies have shown that sites dominated by *B. tectorum* usually have large litter accumulation (Paschke et al. 2000; Ogle et al. 2003). In addition to the effect that litter may have on soil microorganisms and microbial-mediated processes, such as nutrient cycling and decomposition (Bolton et al. 1993; Ogle et al. 2003), litter build up may alter near surface temperature and moisture availability thus affecting germination and survival (Call and Roundy 1991; Chambers 2000). In arid environments, litter accumulation can offer protection from desiccation by reducing evaporation from the soil surface, thus increasing available moisture for germination and establishment (Fowler 1986; Call and Roundy 1991; Noy-Meir and Briske 2002). Beckstead and Augspurguer (2004) observed that when cheatgrass was growing in high densities, a reduction of the surface litter negatively impacted cheatgrass seedling's density and biomass during the establishment phase. During the winter, litter reduction only decreased density whereas no effects were detected during the peak of the growing season. Because, early germination and growth are critical for successful establishment of cheatgrass and other annual invaders (Pyke and Novak 1992; Rice and Dyer 2001), litter accumulation after the first growing season could have favored cheatgrass seedling establishment at the beginning of the second growing season thus, playing a key role in the increased densities and initial seedling growth.

In addition, the residual effects of herbicide application are unknown and may have changed soil nutrient(s) availability (see Chapter 4), which could have influenced cheatgrass responses over time. Because plant tissue data is still being processed we were not able to relate soil nutrient availability to plant density and biomass in order to detect the effect of resource supply in the observed cheatgrass responses.

Although our results support the idea that N availability plays a major role in cheatgrass emergence and establishment, we can not conclude that cheatgrass performance was due solely to changes in N supply. Moreover, we can not exclude the effect that other factor(s) may have in determining cheatgrass responses and competitive ability. Our findings suggest that cheatgrass has facilitated its own establishment thus allowing for population recovery and complete dominance in less than 2 years after the initial reduction due to herbicide and sucrose application.

In general, sucrose application had a strong influence on cheatgrass but did not have such a clear impact on the emergence and establishment of either the perennial native species or Vavilov wheatgrass. These findings supported our initial hypothesis that low nitrogen availability (caused by C addition) would be relatively more detrimental to the annual exotic cheatgrass than to the seeded perennial species, and were consistent with the notion that nutrient limitation typically represents a greater disadvantage for fast-growing exotics like cheatgrass (Young et al. 1998; Paschke et al. 2000; Herron et al. 2001; Ewing 2002) than to the slower growing perennial species (Campbell and Grime 1989).

Although perennial seedling densities were not affected, it is likely that the temporary shortage of soil available N may have affected seedling growth, thus influencing biomass and height (Tilman 1986). Perennial plant measurement data is still being processed, and we were not able to assess species abilities to grow when N was immobilized by the microbial biomass. The only case where sucrose reduced density of native perennial seedlings was observed was in the plots that did not have cheatgrass. It is probable that sucrose effects in the seedlings growing in competition with cheatgrass may have been overridden by higher effects of cheatgrass neighborhood, which, as previously mentioned, may have altered microenvironmental conditions. When biomass data becomes available, we will evaluate if sucrose not only affected seedling density but also height, diameter, or number of tillers.

This experiment revealed a strong dependence of native species on seed availability. Seedling establishment increased with increasing seeding densities for all species except for *E. multisetus* and *S. coccineaI,* which had little or no emergence. Pendery and Rumbaugh (1990) reported that globemallows (*Sphaeralcea* spp.) have potential for rangeland restoration in the Western U.S. We tested the seed viability of *S. coccinea* prior to seeding and adjusted the seeding rate to ensure that we were applying the adequate number of viable seeds m^{-2}. But the lack of establishment of *S. coccinea* at the study site and also in several other distant locations (see Chapter 6-Results) suggests that this particular species could be difficult to establish and its use in restoration should be reassessed.

The overall increase in native perennial establishment as seed availability increased was consistent with results by Sheley et al. (2006) which show higher establishment of native perennial grasses with increasing seeding density in rangelands of the Western US. Based on the observed positive relation between seeding rate and seedling establishment, and also considering the higher densities used by Sheley et al.(2006), we believe that levels of seed addition used in our experiment were a limiting factor for overall native seedling establishment. Moreover, we believe that higher seeding rates could have increased native species recruitment without creating excessive intra- or interspecific competition between seedlings. Because we only seeded Vavilov wheatgrass at one seeding density, we were not able to establish any relation between seeding rate and seedling emergence for this introduced perennial.

In addition to the barrier of seed limitation, the main constrain to perennials establishment in this annual dominated grassland appeared to be competition with cheatgrass. Our results suggest that, when seed availability was less limiting (*i.e.*, when seeding rate was the highest), perennial seedlings were able to establish and coexist with cheatgrass, if cheatgrass density did not exceed more than ~300 plants m^{-2}. At higher cheatgrass densities, native seedling establishment declined. There could be different reasons for these results. First, it is possible that these slower growing perennials were able to tolerate a certain degree of resource limitation when competing with *B. tectorum* at low densities. Second, it seems likely that cheatgrass may have modified the microsite conditions, thus facilitating establishment of the native seedlings (*i.e.*, the relatively low cheatgrass densities during the first growing season may have trapped snow and provided shade and protection from desiccation, thus favoring native seedlings emergence and establishment). Analysis of seedling size could reveal to which degree competition with cheatgrass influenced the growth of native seedlings, even when this annual grass was present at low densities.

Vavilov wheatgrass seedling establishment during the first growing season was affected by cheatgrass density similarly to the native perennials. As a consequence, recruitment was higher when the *Agropyron* seedlings were growing with fewer than 300 cheatgrass plants m^{-2} while reduced establishment was observed at higher cheatgrass densities. Similar to the native perennials, establishment of Vavilov wheatgrass under conditions of low cheatgrass densities may be related to the intrinsic ability of perennial species to withstand a certain degree of resource limitation (Lambers et al. 1998), which in our case could have been induced by rapid resource uptake of cheatgrass.

The general seedling recruitment pattern and the coexistence of both native and introduced perennials with cheatgrass during the first year of the experiment may imply some degree of belowground resource partitioning between the perennial species seedlings and their annual neighbors. Summarizing, the first year results provided evidence that (1) seeding density had a direct effect on the establishment of both cheatgrass and perennial species, and (2) increasing density of cheatgrass negatively impacted the establishment of perennials species' seedlings thus supporting our initial hypotheses.

Despite relatively good initial establishment, plant mortality was high and few perennial seedlings were able to survive through the following growing season. Because sagebrush steppe perennial species seedlings typically exhibit low survival rates (Pyke 1990, Chambers 2000), we were expecting to find fewer seedlings by the second year of the experiment. In our experiment, high mortality in the established seedlings occurred after the first growing season and appeared to be related to the effects of intense interspecific competition and herbivory. First, there was a substantial increase in cheatgrass density, which, on average, increased from ~ 270 plants in the first year to ~2000 plants m^{-2} during the second year. As a result of this increase in cheatgrass density during the second growing season, native seedlings likely supported higher cheatgrass competition for soil resources (*e.g*. water). It is probable that the belowground structures of the native seedlings were not developed enough to withstand such a high degree of competition throughout the entire growing season leading to seedling mortality.

Another consideration is that seedling defoliation consistently occurred throughout the entire study period (M. Mazzola, personal observation). Seedlings are particularly susceptible to herbivory, and herbivores can have a significant effect on plant recruitment and mortality (Huntly 1991). Pyke (1986) observed that defoliation by small mammals can negatively affect the survival of native bunchgrass *Pseudoroegneria spicata* (=*Agropyron spicatum*) seedlings beyond the first year of establishment but does not significantly affect *B. tectorum* populations. Beckstead and Auspurger (2004) also found that even when herbivores consume cheatgrass, they are not effective at controlling its population growth. Because the experiment was not designed to measure the effects of herbivory, we can not estimate the extent of the mortality caused by grazers. Nonetheless, we believe that the combination of continuous grazing by the resident herbivores (*e.g.*; lagomorphs, rodents, grasshoppers) and the intense damage caused by the migratory Mormon crickets at the peak of the growing season may have greatly contributed to the observed perennial seedling mortality. Furthermore, it is likely that the resource limitation (induced by high cheatgrass densities) may have also hindered the ability of the perennial seedlings to compensate the damage caused by the herbivores, thus causing their death.

In the beginning, we proposed that a reduction in cheatgrass competitive ability due to sucrose addition would promote perennial species establishment (*i.e.*, the relaxation of competition would provide a "window of opportunity" for perennial species establishment). Our findings partially supported this hypothesis. Although sucrose addition had a significant influence on cheatgrass, it appeared to have a negligible effect on perennial seedling recruitment. However, the "relaxation of competition" provided by the initially low cheatgrass densities (*via* herbicide application that reduced cheatgrass seed availability) seemed to be critical for the successful establishment of the perennial species during the first year. Survival beyond the first year appears to be controlled by complex interactions of several factors including competition influenced resource supply and herbivory, among others.

CONCLUSIONS

Cheatgrass may exert dominance of a site through a combination of early germination and rapid resource uptake, escape from herbivores, and extremely high seed rain. Our results do not fully explain the mechanisms that allow cheatgrass to dominate the plant community but contribute to the understanding of the factors that influence perennial establishment in cheatgrass invaded sites. The availability of seeds and the level of cheatgrass competition were identified as major constrains to the recruitment of perennial species. Given (i) the lack of reproducing native perennial individuals in invaded ecosystems, (ii) the depleted seed banks of those species, and (iii) the positive responses obtained when seeds were added, the establishment of a continuous source of native seeds over time seems critical to promote ecosystem recovery. It is possible that continuity of the native propagules influx may be more crucial for the recruitment process than the total amount of seeds entering the system in a given year.

Because it is likely that cheatgrass would not be completely eliminated in sagebrush steppe ecosystems, it is important to identify the levels of cheatgrass competition that hinder ecosystem recovery. The importance of understanding the effects of cheatgrass density on the process of native species recruitment should not be underestimated. Our results suggest that native perennials could establish and even benefit from *B. tectorum* presence if cheatgrass levels are relatively low (*i.e.*, less than 300 plants m^{-2} in our site). Therefore, short-term (*i.e.*, more than one year to ensure native perennial establishment) cheatgrass population control without complete elimination may be a more feasible goal for restoration. The results reported in the present Chapter and those reported in Chapter 6 make us to believe that, given adequate environmental conditions and continuous seed availability, *Artemisia tridentata*, *Achillea millefolium*, *Poa secunda*, *Pseudoroegneria spicata*, and *Elymus multisetus* can establish in the neighborhood of cheatgrass. However, because fine fuels typically accumulate in the presence of cheatgrass making the ecosystem more prone to fire, it is important to search and/or develop more fire tolerant genotypes.

Our results suggest that perennials species could be successfully reintroduced into annual grasslands dominated by cheatgrass. Successful restoration will require preserving the surrounding sagebrush habitat remnants as source of seeds in order to restore the seed bank and seed dispersal processes, evaluating the level of cheatgrass competition, assessing the pressure that native herbivores may have during the seedling recruitment stage, and developing plant materials with traits that increase fire tolerance, among others.

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Chapter 8 – Experiment 2: Plant functional groups and Soil N: Secondary weed responses

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INTRODUCTION

Coincident with the continued expansion of annual exotic invasive cheatgrass (*Bromus tectorum*) in the western USA there has been a growing problem of invasion of secondary weeds (Allock et al. 2006). These weeds are considered more noxious than cheatgrass, and it has been speculated that cheatgrass may be helping to facilitate these invasions.

As a further component of Experiment 2 (assessment of plant functional group response to soil N), research evaluated secondary weed species with and without cheatgrass and then in competition with a mixture of native perennials, or with the introduced Siberian wheatgrass (*Agropyron fragile* cultivar Vavilov). In the opinion of the plant materials specialist on the project (Ogle and St. John, Natural Resources Conservation Service), Siberian wheatgrass was chosen as the most competitive introduced perennial grass for these sites. It was used in a similar fashion as crested wheatgrass (*Agropyron cristatum* or *desertorum*) might be used in a location where cheatgrass dominates because of its competitive ablility. This became the standard of comparison for the native mixture.

Because secondary weed species differed among study sites, we limited our evaluations to those present in the local area - Medusahead *(Taeniatherum caput-medusae)* in Idaho and Oregon, rush skeletonweed (*Chondrilla juncea)* in Idaho and squarrose knapweed (*Centaurea virgata)* in Utah.

Many of the weedy species in the Great Basin are thought to be nitrophilous species, therefore, the addition of a labile form of carbon, such as sucrose, should result in an increase in the abundance of microbes in the soil. This increase should lead to immobilization of nitrogen in the microbial community and thus lead to a reduction in biomass and seed production of nitrophilous species, especially annuals (McLendon & Redente 1992).

Our objectives were: (1) determine competitive interactions between desirable perennial species and secondary weeds; (2) assess whether interactions were affected by N availability through the addition of labile carbon in the form of sucrose (hereafter known as sugar), and (3) evaluate interactions between secondary weeds and cheatgrass.

METHODS

We used a split-plot design at each site with two sugar levels (0 or ambient N and 1500 kg sucrose/ha for immobilizing N) as main plots. At each site, 12 large experimental units were established, 6 were seeded in 2003, the other 6 in 2004. Within each set of 6 large experimental units in each year, 3 were randomly assigned to have sugar added to them, 3 were left without any additional sugar. In each of these large experimental units, 10, 2-m x 3-m plots were established and randomly assigned to treatments representing a subset of combinations of 4 factors: seeding or not of a secondary weed (medusahead, rush skeletonweed or squarrose knapweed), cheatgrass, Siberian wheatgrass and a mixture of six native species (*Achillea millefolium, Artemisia tridentata ssp wyomingensis, Elymus multisetus, Poa secunda, Pseudoregneria spicata, Sphaeralcea munroana*). The study using medusahead has two sites and thus will allow inference for sites and years similar to the sites and years used in the overall study, however, the rush skeletonweed and squarrose knapweed studies are case studies with single sites and inference cannot be drawn beyond these sites. For medusahead, 10 combinations of treatments were used to test 5 questions (**Table 8.1**). For squarrose knapweed, 6 combinations of treatments were used to test 5 similar questions (**Table 8.1**). Although rush skeletonweed was seeded in similar combinations to those of medusahead and squarrose knapweed, too few seedlings emerged and survived in treatments to be able to test the questions of interest.

Table 8.1. Plant treatment combinations and their corresponding treatment number in Experiment 2.

Medusahead	Native	Siberian Wht	Cheatgrass	Trt Number
0	1	0	0	9
0	1	0	1	10
0	0	1	0	17
0	0	1	1	18
1	0	1	0	38
1	0	1	1	39
1	1	0	0	40
1	1	0	1	41
1	0	0	0	42
1	0	0	1	43
Knapweed	**Native**	**Siberian Wht**	**Cheatgrass**	**Trt Number**
1	0	1	0	38
1	0	1	1	39
1	1	0	0	40
1	1	0	1	41
1	0	0	0	42
1	0	0	1	43

Plot Sizes and Placement

A 1.0 m^2 plot was permanently marked within each of the seeded plots (**Fig. 8.1**). It was located on the left-hand side of the plot with a 0.25-m border on all sides. A 0.1-m^2 plot was nested within the lower left-hand corner of the 1.0-m^2 plot and permanently marked to count cheatgrass that can be extremely dense. A 0.5 m^2 plot was also marked to count skeletonweed and squarrose knapweed plants that we anticipated might be intermediate in density between cheatgrass and the perennial plants. A second 0.1-m^2 plot was marked in the upper right hand corner of the plot to count medusahead plants.

Census and Cultivation

Census occurred twice during each of two growing seasons. The first census occurred when cheatgrass went into the "boot" stage and the second census occurred when it went into the "purple" stage during each growing season. An additional census was conducted in late fall when fall emergence/green-up was observed (October) during the first year after seeding. All non-target species were removed through hand cultivation from all plots. Cultivation occurred at least once after emergence when species could be identified and before seed maturity in June. Non-target species (unseeded) were also removed during each census and at least once during the summer (~August) and later in the fall (~October). Density at the end of the second growing season was used to answer the following questions using these associated treatments:

For medusahead:

1. Two years after seeding, is Siberian wheatgrass able to reduce medusahead establishment more than is the mix of natives? Treatments 38 through 43.
2. Two years after seeding, does medusahead establish better with cheatgrass than without? Treatments 38 through 43.

For these first two questions, medusahead density was the response variable.

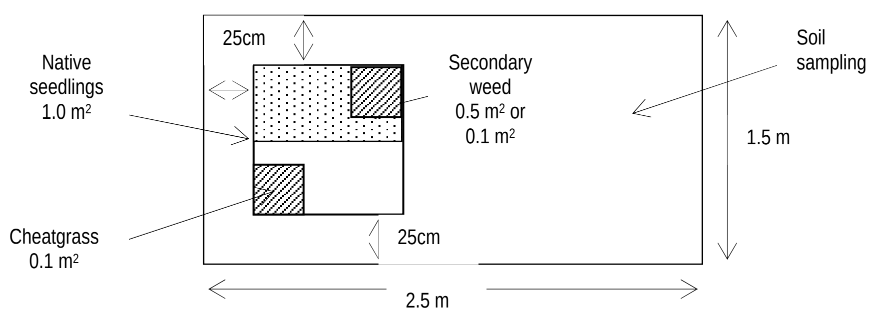

Fig. 8.1. Sampling plot used to assess native perennials, cheatgrass and secondary weeds.

3. Two years after seeding, does the native mix establish better against medusahead or cheatgrass? Treatments 9, 10, 40 and 41.
4. Two years after seeding, does the native mix establish as well or better than Siberian wheatgrass with cheatgrass? Treatments 9, 10, 17 and 18.
5. Two years after seeding, does the native mix establish as well or better than Siberian wheatgrass with the secondary weed? Treatments 9, 17, 38, and 40.

For these last three questions, the density of the native mixture and Siberian wheatgrass are the response variables.

For squarrose knapweed:

1. Two years after seeding, is Siberian wheatgrass able to reduce squarrose knapweed establishment more than is the mix of natives? Treatments 38 through 43.
2. Two years after seeding, does the squarrose knapweed establish better with cheatgrass than without? Treatments 38 through 43.

Similar to medusahead, to answer these first two questions, squarrose knapweed density was the response variable.

3. Two years after seeding, in the presence of squarrose knapweed, does the native mix establish better with or without cheatgrass? Treatments 40 and 41.
4. Two years after seeding, in the presence of squarrose knapweed, does the native mix establish as well or better than Siberian wheatgrass with cheatgrass? Treatments 39, 41, and 43.
5. Two years after seeding, does the native mix establish as well or better than Siberian wheatgrass with the squarrose knapweed? Treatments 38, 40, and 42.

For these last three questions, the density of the native mixture and Siberian wheatgrass are the response variables.

Analyses were run on each secondary weed experiment separately. For medusahead, there were 144 observations analyzed as 2 seeding years (2003 and 2004) by 2 sites Lincoln Bench, OR and Canyon Creek ID) by 2 sugar levels (0 and 1500 kg/ha) by 3 reps of each sugar level by 6 treatments. Since rush skeletonweed and squarrose knapweed were only carried out at one site, the inference is restricted to the separate sites for each secondary weed and to years similar to those of these two years. The effects for these single study sites were tested using variation among years and among replicate of large experimental units giving 72 observations analyzed similar to medusahead as 2 seeding years by 2 sugar levels by 3 reps of each sugar level by 6 treatments. Residuals for models testing each question were checked and assumptions of normality and homogeneous variance were found to be adequately met for medusahead and squarrose knapweed, but the native mixture and Siberian wheatgrass required a natural log transformation (density + 1) to meet the assumptions.

Seed Production and Biomass

Total number of seeds and total biomass of 15 randomly chosen plants (selected at the time of harvest) were determined for each plot in all three sample years from the entire 1.0 m^2 plot. Plants were harvested (preferably from <u>outside</u> the 1m^2 permanent plot) when the seeds were mature but had not dropped (at least the red-stage for cheatgrass). Both seeds and plants were placed in one paper bag, transported to the lab, and allowed to air dry. Seeds were separated from the foliage. The number of filled seeds was recorded and weight of filled seeds determined. Foliage was oven dried to a constant weight at 60 ^{o}C and the weights recorded. Seeds were then returned to plots and broadcast seeded on the surface the following fall, but not raked into the ground.

Total number of seeds of 15 randomly chosen plants (selected at the time of harvest) of each target species was collected (preferably from <u>outside</u> the 1m^2 permanent plot) for each year in which seed production occurred. If fewer than 15 individuals produced seed, the number of individuals reproducing was recorded and seeds collected from all reproducing individuals. Number of filled seeds was recorded and the weight of filled seeds determined. Seeds were returned to plots and broadcast seeded in the fall.

Although these data have been collected, we are still analyzing these results and will only report the findings of the above two-year density study.

RESULTS

Medusahead Response

We found no evidence of any difference among Siberian wheatgrass, cheatgrass or the native mixture in their abilities to reduce establishment of medusahead, either with or without the addition of sugar. Only sugar was found to have a significant effect on the establishment of medusahead seedlings, two years after planting ($F_{1,3}$=11.76, p=0.042). None of the seeding treatments nor their interactions with sugar were found to have a significant effect on establishment (**Fig. 8.2**). Without additional sugar, the median number of medusahead seedlings established per 0.1-m^2 plot was estimated to be between 8.3 and 1015, whereas when sugar was added the estimated median number of seedlings per plot dropped to between 2.7 and 327.5. This represents a reduction in establishment due to addition of sugar of between 8% and 89%.

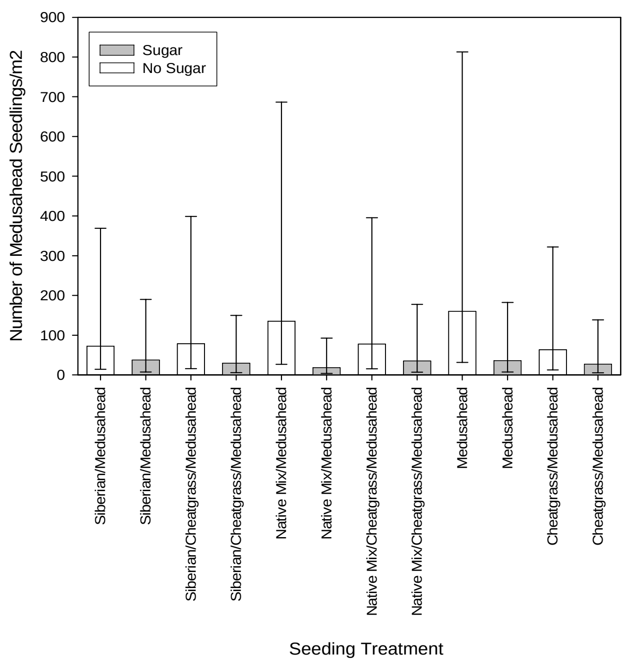

Fig. 8.2. Median (± 95% CI) number of medusahead seedlings with and without sugar and different seeding treatments.

Squarrose Knapweed Response

In contrast to the response of medusahead density, sugar was not found to have a significant effect on the establishment of native seedlings two years after planting ($F_{1,9}$=0.01, p=0.91). However, there were significant differences among the treatments ($F_{5,50}$=2.92, p=0.02), but these differences were similar with or without added sugar ($F_{5,50}$=1.46, p=0.22).

In the absence of any other competitors, the mean number of knapweed seedlings established per 1-m^2 plot when cheatgrass was present was estimated to be between 8.4 and 29.6, whereas when cheatgrass was absent the estimated mean number of knapweed seedlings per plot rose to between 14.5 and 35.6. This did not represent a statistically significant reduction in establishment due to presence of cheatgrass (t_{50}=1.79, p=0.08). When Siberian wheatgrass was sown, the mean number of knapweed seedlings established per 1-m^2 plot when cheatgrass was present was estimated to be between 3.6 and 24.7, whereas when cheatgrass was absent the estimated mean number of Siberian wheatgrass seedlings per plot rose to between 6.9 and 28.1. This did not represent a statistically significant reduction in establishment due to presence of cheatgrass (t_{50}=0.98, p=0.33). When native plants were sown, the mean number of knapweed seedlings established per 1-m^2 plot when cheatgrass was present was estimated to be between 3.4 and 24.5, whereas when cheatgrass was absent the estimated mean number of knapweed seedlings per plot rose to between 8.9 and 30.1. This did not represent a statistically significant reduction in establishment due to presence of cheatgrass (t_{50}=1.64, p=0.11). The significant plot effect was not due to addition of cheatgrass (**Fig. 8.3**).

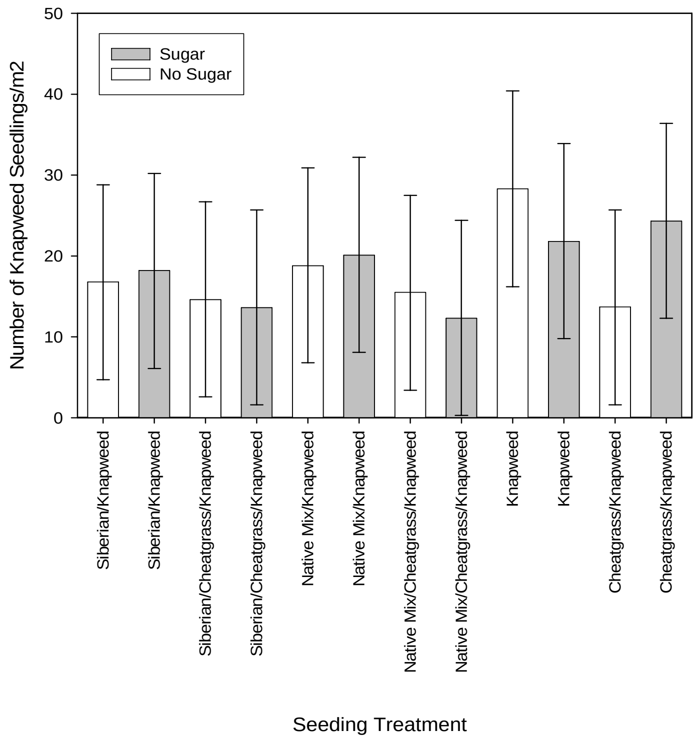

Fig. 8.3. Median (± 95% CI) number of knapweed seedlings with and without sugar and different seeding treatments.

Native Mixture vs. Medusahead or Cheatgrass

Sugar was not found to have a significant effect on the establishment of native mixture or the Siberian wheatgrass seedlings two years after planting ($F_{1,3}$=0.0, p=0.95). Presence of medusahead and cheatgrass both reduced native seedling establishment ($F_{1,3}$=7.9, p=0.01 and $F_{1,3}$=170.6, p=0.005, respectively), but their effects were not interactive with each other nor with sugar. Thus the native mix establishment did not differ when grown with either weedy species.

The median number of native seedlings established per 1-m^2 plot when medusahead was absent was estimated to be between 2.5 and 9.2, whereas when medusahead was present the number decreased to between 1.5 and 5.5. This represents a reduction in establishment due to presence of medusahead of between 12% and 59% (**Fig. 8.4**). The median number of native seedlings established per 1-m^2 plot when cheatgrass was absent was estimated to be between 2.8 and 10.4, whereas when cheatgrass was present the number decreased to between 1.3 and 4.9. This represents a reduction in establishment due to presence of cheatgrass of between 32% and 68% (**Fig. 8.5**).

Native Mixture vs. Siberian Wheatgrass with Cheatgrass and Medusahead

We also compared the native mix establishment with the establishment of Siberian wheatgrass to determine if the natives established as well or better than Siberian wheatgrass when grown with cheatgrass or medusahead both with and without sugar. These separate tests (one for the native mix and one for Siberian wheatgrass) showed similar results. Sugar did not impact establishment of either the native mixture or of Siberian wheatgrass ($F_{1,3}$=2.08, p=0.19 for natives; $F_{1,3}$=0.68, p=0.47 for Siberian wheatgrass). Cheatgrass and medusahead each reduced the establishment of natives and Siberian wheatgrass ($F_{3,42}$=9.68, p<0.001; $F_{3,18}$=6.33, p=0.004 for medusahead), but these differences were similar with and without added sugar ($F_{3,42}$=0.41, p=0.75 for cheatgrass; $F_{3,18}$=1.19, p=0.34).

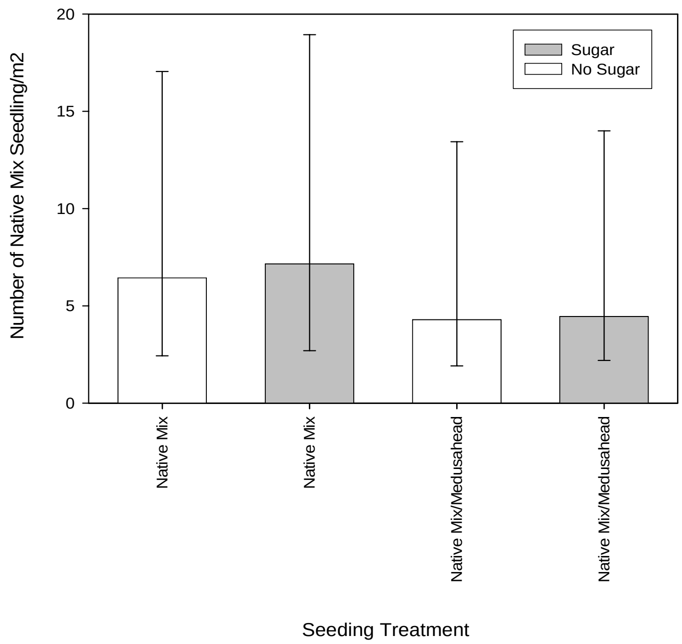

Fig. 8.4. Median (± 95% CI) number of native mix seedlings with and without sugar and medusahead.

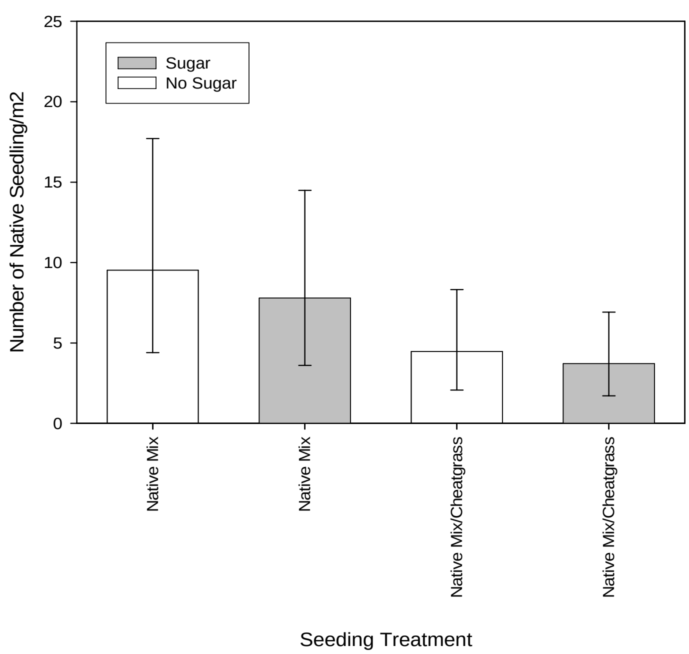

Fig. 8.5. Median (± 95% CI) number of native mix seedlings with and without sugar and cheatgrass.

When grown with cheatgrass, the native mixture was reduced between 27% and 69%, whereas Siberian wheatgrass was reduced between 12% and 63%. When grown with medusahead the native mixture establishment was not reduced significantly (between 1.9 and 10.2 with medusahead and 2.9 and 15.8 without medusahead) (**Fig. 8.4**). Siberian wheatgrass was reduced between 42% and 82% when grown with medusahead (between 4.5 and 24.2 without medusahead and between 1.4 and 7.7 with medusahead) (**Fig. 8.7**). However, there was no detectable difference in the magnitude of the reduction of establishment of native seedlings relative to Siberian wheatgrass due to cheatgrass (t_{42}=-0.60, p=0.55) or due to medusahead (t_{18}=1.75, p=0.10).

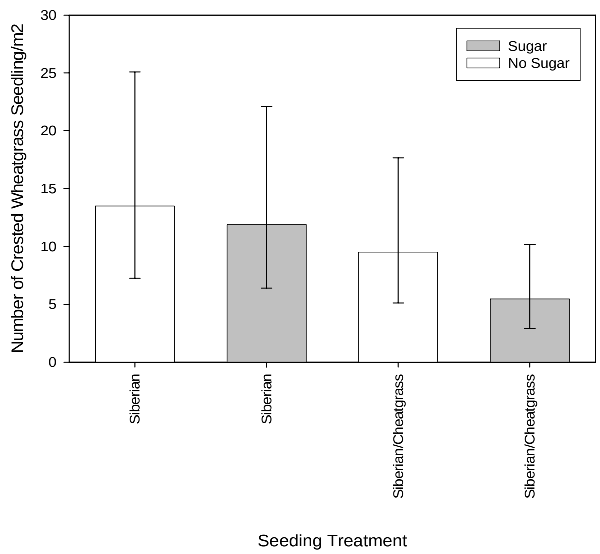

Fig. 8.6. Median (± 95% CI) number of Siberian wheatgrass seedlings with and without sugar and cheatgrass.

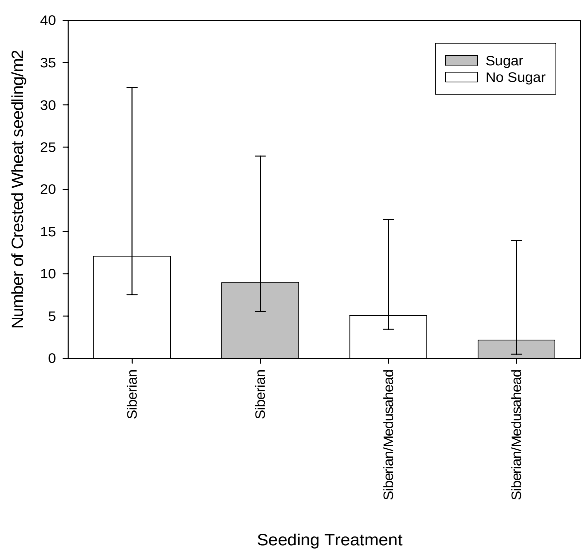

Fig. 8.7. Median (± 95% CI) number of Siberian wheatgrass seedlings with and without sugar and medusahead.

Native Mixture with Knapweed with and without Cheatgrass

Sugar was found to have a marginally significant effect on the establishment of native seedlings two years after planting ($F_{1,9}$=5.45, p=0.04). There were no significant differences among the cheatgrass treatments ($F_{1,10}$=0.93, p=0.36) nor of their interaction with sugar ($F_{1,10}$>0.01, p=.97). The median number of native seedlings established per 1-m^2 plot at this site when sugar was not added was estimated to be between 2.9 and 19.7, whereas when sugar was added the number dropped to between 1.6 and 8.6. This represented a statistically significant reduction in establishment due to addition of sugar (t_9=2.34, p=0.04) of between 13% and 80% (**Fig. 8.3**).

Native Mixture vs. Siberian Wheatgrass in the Presence of Knapweed with and without Cheatgrass

None of the factors (sugar, cheatgrass or their interaction) was found to have a significant effect ($p<0.21$) on the establishment of native or Siberian wheat seedlings, two years after planting. The median number of native seedlings established per 1-m^2 plot at this site was estimated to be between 1.7 and 14.8, and the median number of Siberian wheatgrass seedlings established per 1-m^2 plot was estimated to be between 1.1 and 10.0 (**Fig. 8.3**).

DISCUSSION

Cheatgrass currently dominates more than ~2 million ha of lands in the Great Basin (Bradley & Mustard 2005). To our knowledge, this is the first study to attempt to investigate the potential for cheatgrass to facilitate the establishment of other secondary weeds within the Great Basin. We found no evidence for facilitation of medusahead or of knapweed in our studies. Our studies only examined one aspect of the facilitation question since all of our studies were conducted on lands currently occupied by infestations of cheatgrass. We did not compare establishment of these secondary weeds on lands that have not been dominated by cheatgrass. We recommend that this comparison also be conducted on sites where cheatgrass has not dominated the site because the dominance of cheatgrass may change ecological processes in the soil (see citations and results from DeCrappeo and Pyke Chap 3 and Blank and Norton Chap 4 of this report). This additional comparison would determine if the presence of cheatgrass improves the invasion success of secondary weeds.

Introduced forage grasses, such as Siberian wheatgrass are often recommended for rehabilitation of rangelands dominated by invasive annual plants within the Great Basin. They have been found to establish well and are competitive and in some cases may reduce the annuals (Asay et al. 1985, Francis & Pyke 1996). Although our results showed that cheatgrass and medusahead both reduced establishment of the native mixture and of Siberian wheatgrass, we did not find evidence to support enhanced establishment of Siberian wheatgrass over that of the mixture of the native species. There might be other factors that might contribute to Siberian wheatgrass success, but our study indicated that for this species of Siberian wheatgrass, establishment of two-year-old seedlings did not differ from that of the native mixture.

The addition of carbon in the form of sugar appeared to be more of a factor in reducing establishment for the two invasive annual grasses, cheatgrass and medusahead, than it was for squarrose knapweed. It is thought that the additions of labile forms of carbon result in increases in the heterotrophic microbial community which in turn immobilize nitrogen making it less available for fast growing plants such as cheatgrass and medusahead. Most previous studies have examined the effect of adding labile forms of carbon on the mass and seed production of annual grasses (Witwicki 2006, McLendon & Redente 1992, Blumenthal et al 2002), however our results are showing reductions of establishment of reproductive plants of the cheatgrass and medusahead into the second year after the sucrose treatment. This could result from an initial reduction in biomass and seed production in the first year after the sugar application, being carried forward into the second year as a reduction in numbers of plants in the plots. Thus, labile carbon additions might provide a 2-year window of reduced competition both by reducing the sizes of plants in the first year and by reducing the population of invasive annual grasses in the second year.

The lack of an impact of sugar additions on squarrose knapweed was unexpected, but may relate to later phenology translating into avoiding the reduction in nitrogen or it may be tolerant of low nitrogen environments. We will need to examine the first year results and the biomass and seed production of this species to gain a better explanation of the results.

Large expanses of the Great Basin are now dominated by invasive annual grasses with the invasions of other weedy species becoming more problematic since they appear to be invading areas where cheatgrass already exists. Cheatgrass is known to be a strong competitor against native plants in the Great Basin, but we can no longer expect that it will remain as a stable community in the Great Basin. Other species of invasive plants may arrive and become established as well, creating a more diverse, new community that may continue to develop. To this moment, we have no evidence that cheatgrass is facilitating these additional invasions. However, on the positive side, we have shown that native mixtures of species can establish as well as Siberian wheatgrass. This provides hope for those that wish to restore native plants into these invasive plant-dominated communities. The potential for the native plants or for Siberian wheatgrass to eventually totally exclude these invasive plants is not likely, thus we need to study how managers should best manage lands with restored natives to allow them to coexist with these invasive plants.

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Chapter 9 – Integrated statistical strategies: Making sense of site and year differences

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INTRODUCTION

Our multi-state, multi-agency project was designed to test methods of cheatgrass control and native species restoration across a range of sites and conditions throughout the Great Basin. One of the unique and powerful aspects of this project is the distribution of experimental units across four states in the Great Basin. This gives us the ability to better understand ecological interactions and to generalize our results over a broad area; it also brings challenges in terms of data synthesis, analysis and interpretation.

While large-scale studies such as this one are essential for understanding ecological processes and for designing appropriate management and restoration projects, there are difficulties in analyzing data from such studies. One of the primary difficulties arises because it is difficult to replicate large-scale experiments adequately, and if there is substantial replication there is usually also substantial variation among replicate sites. To account for this variation, researchers often collect large amounts of information about the site, with the intention of using these additional variables as covariates in a standard linear modeling context (such as ANOVA, ANCOVA or GLM analyses). Unfortunately, it is often the case that there are more covariates than replicates, thus dramatically limiting the power of a standard statistical model to detect experimental effects and site differences. In addition, experimental effects may be subtle enough that no significant effects are detected using standard statistical methods, given the level of replication that was possible in the study. Sites could be analyzed separately, but this reduces the generality of application for the study results and makes it difficult to understand possible differences in site responses (except in an anecdotal way).

Fortunately, there are a number of techniques that can be employed to help overcome these limitations and maximize both the power and generality of large studies. We will explore three different approaches to our large data set. First, we will use multivariate data reduction (ordination) to compress our many covariates into one or two 'composite predictor variables' which can be used in a traditional mixed linear model without sacrificing too much power. Second, we will treat each individual site and experimental iteration as an independent experiment, using formal meta-analysis to test for experimental effects. Third, we will create structural equation models (SEMs) to investigate mechanistic relationships between our environmental and biotic data sets.

Mixed Models and Composite Predictor Variables

Because we repeated the same split-plot factorial experimental design at each site, we can use mixed linear models to test our specific experimental treatments and hypotheses (*e.g.* Chapter 6 of this report). This will allow us to generalize our findings across a large area, but because of the limitations inherent in such a project (the power is necessarily low because of the cost of sampling many areas and the difficulty of finding and establishing study sites at many locations), relying exclusively on a mixed-model ANOVA framework will only allow us to see large effects rather than subtle ones. We can possibly increase our resolution by including environmental variables as covariates. Since we have limited degrees of freedom to test for site differences or to account for site-related environmental effects, we need to carefully choose the covariates we use, and/or combine these variables into 'composite predictor' variables using multivariate methods (McCune 1997). In this case, we used principal components analysis (PCA) to extract ordination axes that contained a combination of the information provided by our covariates. We then used the vector of PCA scores along the first ordination axes as covariates in our mixed model.

Meta-analysis

We can also take a different approach, treating each site and each repetition of the experiment as a separate study and conducting formal meta-analyses (Gurevich and Hedges 2001, Rosenberg et al 2000). In meta-analysis, we calculate 'effect size' (a measurement that portrays the extent to which a given effect is present in a sample – Rosenberg et al 2000) at each site separately. We then compile these effect sizes to estimate the overall strength of the effect (and the variance of this estimate), and then determine whether this overall effect is greater than would be expected by chance. Additionally, effect sizes added to the meta-analysis are weighted based on the variance associated with the individual study and the sample size used to create the estimate. Because meta-analytical models are actually general linear mixed models (GLMMs – Rosenberg et al 2000), it is possible to also incorporate some data structure (*e.g.* grouping variables and covariates) into the analysis. One of the advantages of meta-analysis is that it is a cumulative technique. This means that even if individual studies do not find a statistically significant result, if the effect is all in the same direction, the combination of studies may indicate a significant effect for a given factor.

Structural Equation Modeling

Ultimately, we want to understand how the different components of the ecosystem we studied interact. We can use information about site characteristics, soils, climate, and vegetation to help elucidate mechanistic relationships using structural equation modeling (SEM – Bollen, 1989). SEMs are systems of linear equations used to determine causal relationships between sets of variables and are related to path and factor analysis. They include both 'latent' variables and 'observed' or 'manifest' variables. Latent variables relate to concepts and are hypothetical or abstract (they cannot be measured directly and thus are free of measurement errors). Manifest variables are the measurable variables that describe the latent variable and are subject to measurement error. For example, 'climate' is a latent variable; 'annual precipitation', 'heating degree days' and 'evapotranspiration rate' would be among the associated manifest variables. SEM consists of creating a path diagram indicating hypothesized causal relationships between latent variables and indicating the manifest variables that relate to each latent variable. A multivariate system of equations is created based on the path diagram, and factor loadings for each path are computed. The appropriateness of the factor loadings can be tested by creating the model based on a 'training' data set (a subset of the available data) and then testing the model fit against a 'testing' data set. SEMs differ from traditional mixed model analyses in two important ways. First, they specifically look for causal, mechanistic relationships among multiple variables; and second, in SEM it is beneficial to have numerous manifest variables in order to better describe the latent variables. SEM is still subject to the need for adequate data points in order to create reliable factor loading estimates however. According to Tanaka (1987), some authors suggest sample sizes as low as 20-50 can result in robust models, but the reliability of the Maximum Likelihood estimation technique used in SEM may break down when sample size is below 100. While there is no simple way to determine adequate sample size, t is clear that the stability and reliability of model fit statistics are affected by the number of subjects in the model, especially the ratio of sample size to the number of estimated parameters (Tanaka 1987). This requirement may limit our ability to apply SEM successfully in our study.

METHODS

The study areas, experimental designs, and data collection methods and available datasets for the experiments analyzed here are described in Chapters 1-8 of this report. In addition to the soils, soil fauna, weather, and plant data collected at each site, we used the PRISM climate data base (http://mistral.oce.orst.edu/www/mapserv/nn/index.phtml) to extract precipitation and temperature information for each study site for the duration of the study.

Mixed Models and Composite Predictor Variables

We grouped our environmental and site variables (covariates for the seeding experiments) into categories based on the applicable experiment, the sampling area (individual plots VS sites), the type of data (soil or climate), and the mutability of the data with our treatments (rapidly changing VS unchanging). The groups of data were: (a) soil variables collected at the site level, including C:N ratio, % organic matter, % clay and % sand; (b) weather variables, including growing season precipitation (annual precipitation compiled from October through September), air temperature (growing degree days), and gravimetric soil water; (c) sugar-affected variables sampled at the whole-plot level for experiment 2, including pH, resin-extractable nitrate, resin-extractable manganese, resin extractable orthophosphate, and the first two axes from the multivariate analysis of soil microbial communities (Chapter 5 of this report); (d) soil crust variables measured at the whole-plot level for Experiment 1, including % vascular plant cover, % moss, % lichen, % cyanobacteria, % litter, % bare soil, and % physical crust (slake test results were not available for all sites, and were omitted); and (e) soil nutrient and microbial effects variables for Experiment 1 (compiled for each site from initial data from the no-sucrose-added plots in experiment 2), including pH, resin-extractable nitrate, resin-extractable manganese, resin extractable orthophosphate, and the first two axes from the multivariate analysis of soil microbial communities.

Since not all data sets were complete at the time of this report, we chose our most complete data set to conduct an initial trial 'composite predictor' analysis, and focused on the 2004 sampling data from Oregon, Idaho, and Nevada from Experiment 1. We compiled data sets corresponding to each of our proposed composite variable types, and then conducted principal components analysis on standardized data to extract composite variables that captured the maximum possible information about site and plot differences (PC-Ord, MjM Software 1998). At the time of this analysis we had not yet extracted degree-day information from the PRISM data base, so we did not create a weather composite predictor; instead we simply included the actual annual precipitation value as a covariate in our analysis. We compiled data to create soil composite predictor variables (SCPV) and nutrient composite predictor variables (NCPV) for each site, and soil crust composite predictor variables (CCPV) for each whole plot.

We then conducted a mixed generalized linear model analysis using a stepwise model-building procedure and comparing AIC values to determine which covariates should be included in the final model (SAS 9.1, SAS Institute Inc., 2002). We used log-transformed density of sown species as the response variable. When we conducted our mixed model analysis, we used the following covariates in addition to our experimental factors of herbicide application and seeded species: density of cheatgrass, density of other species, growing season precipitation, soil moisture in March 2004, and our composite predictor variables (the first two PCA axes from each ordination) SCPV1, SCPV2, NCPV1, NCPV2, CCPV1, and CCPV2. Although we used ordination to reduce the number of covariates in our models, there were still many more variables and interactions than available degrees of freedom to test these, so we were not able to include all interactions. Instead we carefully considered which interactions and main effects were likely to be biologically important and interesting, and included only these in the mixed model. We included the following interactions: cheatgrass density by precipitation, cheatgrass density by planted species, cheatgrass density by precipitation by planted species, other density by precipitation, other density by planted species, other density by precipitation by planted species, herbicide treatment by precipitation, herbicide treatment by planted species, and precipitation by planted species. Denominator degrees of freedom were determined by the Kenward Rogers estimation method.

Meta-analysis

We used Experiment 2, testing the effect of sucrose application on cheatgrass seed production in the first season after seeding (2004 data for 2003 seedings, and 2005 data for 2004 seedings), as an example of applying meta-analysis to a large replicated study.

We considered each planting treatment (the 6 native species in monoculture, the native species mix, cheatgrass seeded alone, and Siberian wheatgrass) at each site to be a separate 'study' for the purposes of the meta-analysis. We calculated mean seeds per plant and the variance in this value for un-sugared plots ('control') and sugared plots ('treatment') with a sample size of N=3 (three sugared or non-sugared plots per site) . We used these values to create an effect size for sucrose application for each of the planting treatments. We chose 'hedge's d' as our effect size (this is the difference between the treatment and control means scaled by the pooled standard deviation and sample size; Rosenberg et al

2000). We used Meta-Win statistical software (Rosenberg et al 2000) to calculate effect sizes and then conduct mixed-model meta-analyses first with no grouping variables (to estimate overall effect size and determine if there was heterogeneity among 'studies' in the analysis) then with seed year as a grouping variable, planted species as a grouping variable and finally with site as a grouping variable. For each analysis we generated an effect size for each group, bootstrap confidence intervals surrounding the effect size, and overall and within-group Q statistics indicating the heterogeneity among estimated effect sizes. The Q values can be compared against a Chi-squared distribution to determine whether there is significant heterogeneity among effect size estimates within a given grouping (Rosenberg et al 2000).

Structural Equation Modeling

This analysis is currently underway. We constructed path diagrams for Experiment 1, the core component of Experiment 2, the density component of Experiment 2 and the secondary weed component of Experiment 2 (see **Figs. 9.1 and 9.2** for examples). We are conducting factor analyses on the data sets used in our 'composite predictor variable' analyses. Once all data for the studies have been processed and compiled, we can begin refining the SEMs.

RESULTS

Mixed Models and Composite Predictor Variables

The first ordination axes for each PCA explained proportions of variance ranging from 39% for soil crust variables to 81% for soil nutrient variables. For the site soil characteristics PCA1 explained 52% variance among sites, and there were negative eigenvalues for all component variables. PCA2 explained 26% variance, with negative eigenvalues for C and C:N, and positive values for sand and clay. For the soil crust variables, PCA1 explained 39% variance among plots, with negative eigenvalues for bare ground and physical crust, and positive eigenvalues for all other variables (highest for moss). PCA2 explained 24% variance, with a negative eigenvalue for litter and positive eigenvalues for all other variables (cyanolichen highest). For soil nutrient variables, PCA1 explained 81% variance among sites, with a positive eigenvalue for manganese and negative for all others. PCA2 explained 11% variance, with positive eigenvalues for all components, but highest for orthophosphate.

When we ran our mixed model analysis including all the covariates listed in the methods section of this chapter, the AIC was 4760, and the simple mixed-model ANOVA with no covariates had an AIC of 4784, indicating that addition of covariates made a slight improvement in model fit, but that the degrees of freedom used by adding a large number of covariates reduced the efficiency of the model. Using a stepwise selection procedure (systematically removing and re-inserting covariates, and re-running the analysis with different variable combinations) we were able to find a best-fit model, with AIC of 4529. This best-fit model included cheatgrass density, other density, precipitation, both nutrient composite predictors (NCPV1 and NCPV2), the first soil composite predictor (SCPV1), cheatgrass density by sown species, other density by sown species, cheatgrass density by sown species by precipitation, other density by sown species by precipitation, and precipitation by herbicide treatment. The ANOVA table from this model is shown in **Table 9.1**.

Table 9.1: analysis of variance output for mixed model analysis of sown species density in 2004 in Experiment 1. Factors in bold had significant effects on the density of sown species.

Factor	Num DF	Den DF	F	p
SPECIES	**11**	**768**	**4.07**	**<.0001**
TRT	1	6.95	0.89	0.3783
TRT*SPECIES	**11**	**755**	**2.37**	**0.0070**
BRTE	1	493	0.09	0.7603
OTHER	1	156	0.10	0.7583
OTHER*PPT*SPP	**12**	**723**	**2.65**	**0.0017**
PRECIP	**1**	**8.33**	**5.14**	**0.0519**
PRECIP*TRT	1	6.93	0.49	0.5086
BRTE*SPECIES	**11**	**764**	**2.65**	**0.0024**
PRECIP*SPECIES	**11**	**759**	**3.92**	**<.0001**
BRTE*PPT*SPP	**12**	**755**	**2.39**	**0.0050**
NCPV1	**1**	**5.84**	**33.82**	**0.0012**
SCPV1	**1**	**5.45**	**49.45**	**0.0006**
NCPV2	**1**	**4.31**	**32.04**	**0.0038**

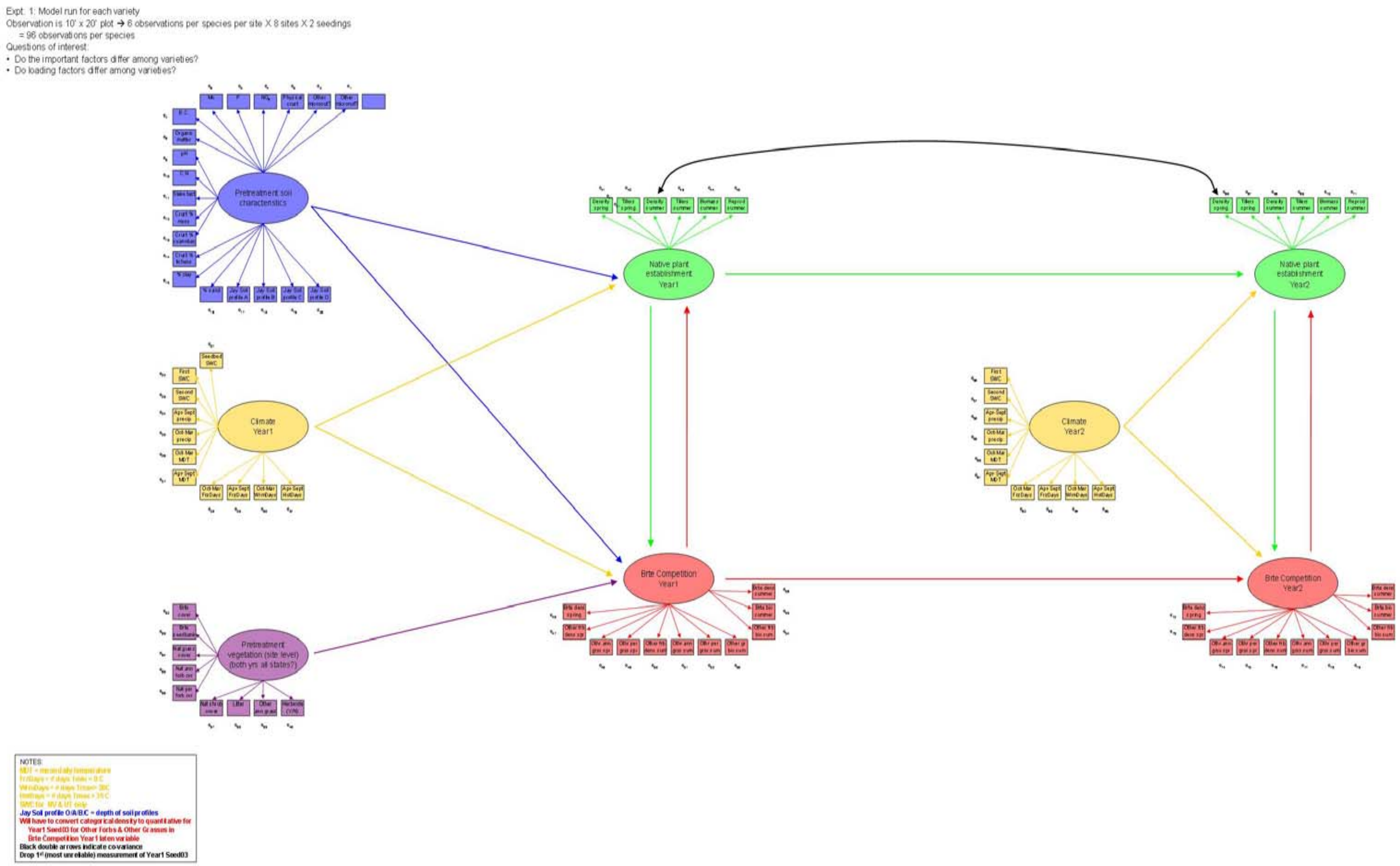

Fig. 9.1. SEM path diagram for Experiment 1

Seeded species differed significantly in their final density in 2004, and species responded differently to herbicide treatment. There was a significant three-way interaction between density of 'other' species, seeded species, and precipitation. Density of seeded species was marginally dependent on precipitation, and there was a significant interaction between seeded species and precipitation. Seeded species differed in their relationship to cheatgrass density (significant interaction term), and there was a significant three way interaction between cheatgrass density, seeded species, and precipitation. Interestingly, all three composite predictor variables that were selected by the model selection procedure were highly significant predictors of seeded species density, indicating that site-related soil differences may be very important for seedling establishment.

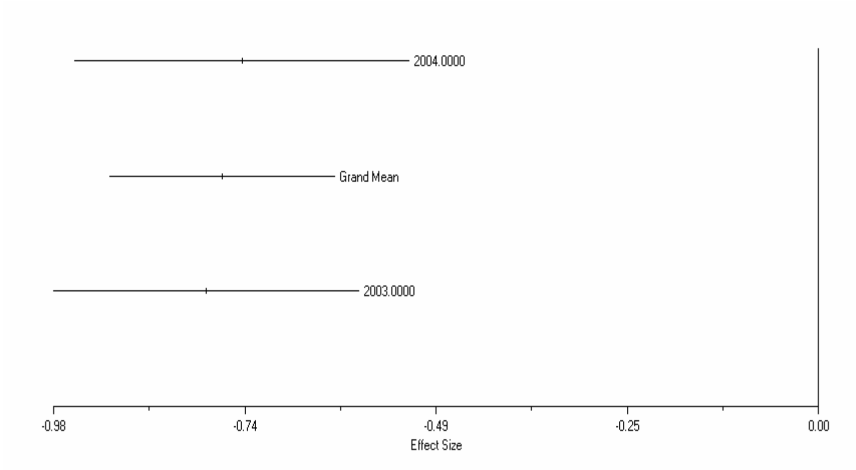

Fig. 9.2. Effect sizes and confidence intervals for meta-analysis of sucrose effect on cheatgrass seed output per plant, 'studies' grouped by seeding year.

Meta-analysis

The overall meta-analysis showed a significant negative effect size of sugar application on cheatgrass seed production per plant (Effect size -0.7675, 95% bootstrap CI -0.9104 to -0.6283). There was marginally significant heterogeneity in the data set (Q_{total} = 175.7188 for 147 degrees of freedom, p = 0.053). When the data were analyzed with seed year (2003 or 2004) as a grouping variable, the two seed years did not differ significantly in their effect size ($Q_{between}$ = 0.0974, p = 0.75, **Fig. 9.2**) but there was significant heterogeneity among 'studies' from each year (Q_{within} = 175.6214, p= 0.048). When the data were analyzed with seeded species as a grouping variable, the species treatments did not show a significant difference in effect size ($Q_{between}$ = 5.6433, p = 0.77502, **Fig. 9.3**) but there was significant

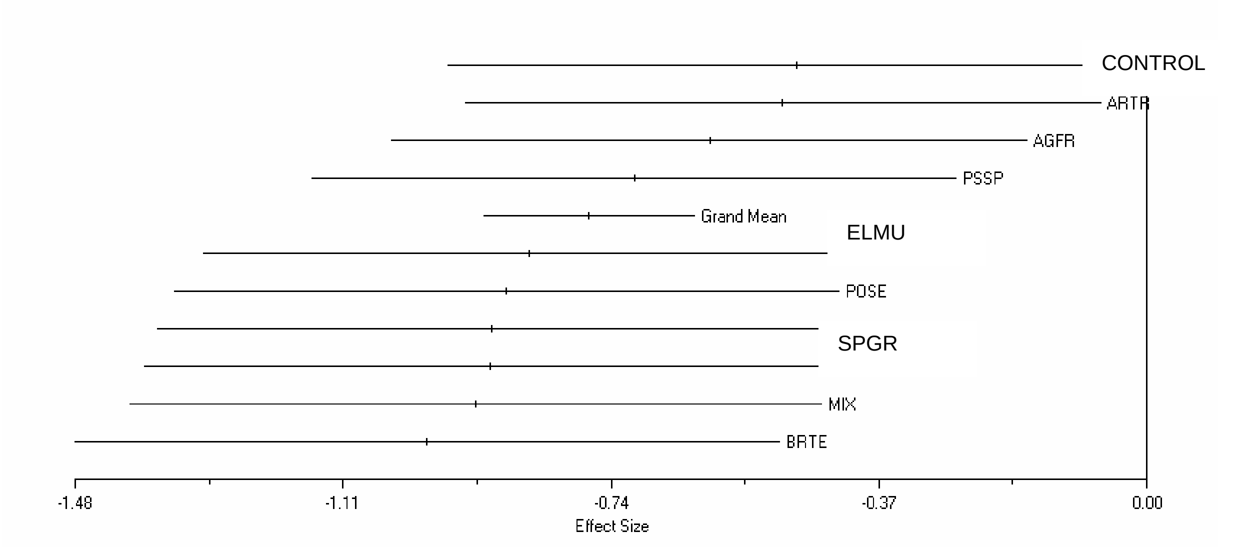

Fig. 9.3. Effect sizes and confidence intervals for meta-analysis of sucrose effect on cheatgrass seeds per plant, 'studies' grouped by seeded species treatment. CONTROL = no seeding, ARTR = *Artemisia tridentata*, AGFR = *Agropyron fragile* ('Vavilov' crested wheatgrass), PSSP = *Pseudoroegneria spicata*, ELMU = *Elymus multisetus*, POSE = *Poa secunda*, ACMI = *Achillea millefolium*, SPGR = *Sphaeralcea grossularifolia*, MIX = six native species mix, and BRTE = *Bromus tectorum* seeded alone.

heterogeneity among studies within the groups (Q_{within} = 170.0755, p = 0.033). When the data were analyzed using sites as a grouping variable, there were significant differences in the effect sizes at different sites ($Q_{between}$ = 17.4928, p = 0.014, **Fig. 9.4**) and studies within groups were homogeneous (Q_{within}=158.2260, p = 0.13903).

CONCLUSIONS

Although we are still early in our attempts to create general models across sites in this study, we have some promising outcomes. First, we were able to compress our many environmental covariates into a reduced number of composite variables and produce an informative mixed model. Analyzing the data in this way highlighted the potential importance of soil nutrients and precipitation in explaining differences in results among sites, accounted for the potential competitive relationship between our seeded species and background vegetation, and also helped clarify the significance of our experimental treatments in the light of environmental variation. Second, we can see from our meta-analysis that the two iterations of our experiment had very similar results (thus we can combine the data in subsequent analyses) and most of the variation in outcome was due to differences in effect size at different sites (in particular, a strong negative effect size at Eden Valley NV, and a less negative effect size at Cindercone Butte ID and Succor Creek OR). Now that we have seen systematic and explainable differences among sites, proceeding with structural equation models appears to be an ideal way to determine mechanistic relationships among the components of the ecosystems.

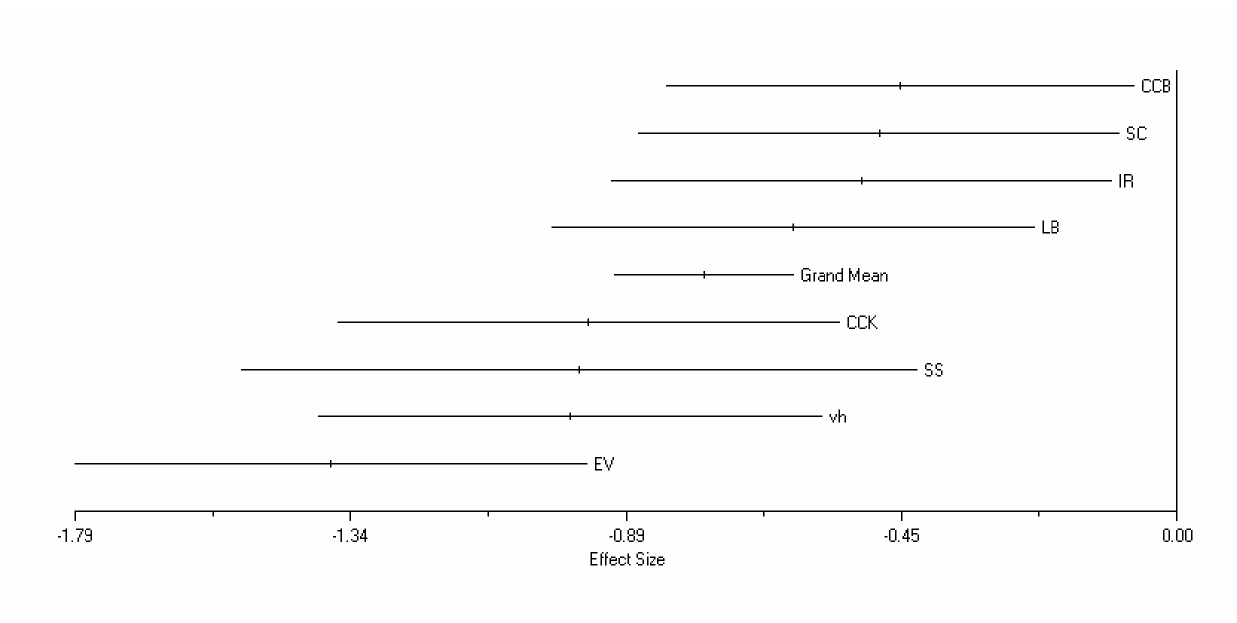

Fig. 9.4 Effect sizes and confidence intervals for meta-analysis of sucrose effect on cheatgrass seeds per plant, 'studies' grouped by site. CCB = Cindercone Butte ID, CCK = Canyon Creek ID, EV = Eden Valley NV, IR = Izzenhood Ranch NV, LB = Lincoln Bench OR, SC = Succor Creek OR, SS = Simpson Springs UT, VH = Vernon Hills UT.

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Chapter 10 – Experiment 3: Applications to larger scales

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INTRODUCTION

Two biological features that contribute to the remarkable success of cheatgrass are prolific seed production and high competitive ability (Smith *et al*. 1997). Thus, restoration strategies for Great Basin rangelands must first promote the reduction of cheatgrass populations by reducing the abundance of cheatgrass seed, and subsequently establishing native species that are competitive with cheatgrass (Young *et al* 1987). Seed production by cheatgrass can be 10-100 times greater on burned sites in the first year after fire, and although population density may be relatively small during this first year after a fire, field and modeling studies demonstrate that cheatgrass populations have an 80-90% risk of exploding to densities near 10,000 plants m^{-2} within 10 years (Young & Evans 1978; Pyke 1995).

Experiment 3 was designed to investigate the effectiveness of different restoration treatments at a management level scale in an area where cheatgrass is a significant portion of the understory. Four potential methods to control cheatgrass were investigated: (1) experimental seeding without treatment (*i.e.* seeded control); (2) true control to test for fence effect (*i.e.* unseeded control); (3) a seed-burn-seed treatment targeted to reduce both the cheatgrass seed bank and cheatgrass' access to available soil N; and (4) a herbicide treatment to serve as an experimental reference point. Following experimental treatments, 1 of 2 seed mixtures was applied: (1) 6 accessions that performed well in Experiment 1 and were thought to be successful at Experiment 3 restoration sites (these seedings represent a transition community from cheatgrass to the desired native plant community) and (2) the same seed mix used in the competitive interactions studies (Experiment 2).

The seed-burn-seed treatment is designed first to reduce weed seed production, then to deplete available soil N. A cover crop of Triticale (annual sterile wheat/rye hybrid) was seeded to provide competition with cheatgrass for water, space, and soil N, and to provide fine fuels to carry the prescribed burn. The burn was a low-intensity head fire designed to further reduce the cheatgrass seed bank as well as to volatilize nitrogen, and the second seeding was the final seed mix (from Experiment 1 or 2). Because herbicide restoration treatments have a high success rate in controlling cheatgrass before restoration, they serve as an experimental standard to judge the relative success of the other treatments. Round-up® was used because of its relatively short half-life and low toxicity. Unseeded controls are included to measure the effect of fencing alone on plant communities, and seeded controls compare the difference between treatments, and native seeding alone.

The overall goal of this restoration experiment is to determine the relative success of restoration strategies that incorporate prescribed methods to control cheatgrass competition and its prolific seed production. Our objectives are: (1) determine if prescribed fire reduces cheatgrass competition for available soil N and seed bank, and thus enhances the establishment of native species; (2) determine if the presence of secondary weeds influences the control of cheatgrass and establishment of natives; (3) determine whether a transition community of competitive natives can be established more readily than a diverse community of different growth forms; and (4) understand the underlying ecological mechanisms for the observed results.

With these studies, we seek to answer the following research questions: (1) How do the pre-treatments (seed-burn, herbicide) affect weed seedbanks?; (2) How do site preparation treatments affect soil nutrients?; (3) How do treatments affect establishment of natives? (4) How do the treatments (seed-burn, herbicide) affect weed density / biomass / reproduction in the following growing season?; (5) Do the seed mixtures differ in their establishment?; and (6) Do the seed mixtures differ in their suppression of cheatgrass?

METHODS

Site Description

The Bedell Flats site is part of a BLM allotment off of Hungry Valley Road, northeast of Reno, Nevada (**Fig. 10.1**). It is located within the Bedell Flats quadrat (T23N/R19E. sections 24, 25, 26, and 36) and includes two fenced regions encompassing 117.9 and 316.2 acres respectively. Primary use of this site was as a grazing allotment, with secondary uses including off-road vehicle use and target shooting.

The site burned in the summer of 2000 and was subsequently seeded by the BLM. Seeded species include Critina Thickspike wheatgrass (*Agropyron dasystachyum*), Hycrest Crested Wheatgrass (*Agropyron cristatum*), Arriba Western Wheatgrass (*Agropyron smithii*), Four-wing Saltbush (*Atriplex canescens*), and Ladak Alfalfa (*Medicago sativa*). The Washoe County Nevada South Part soil survey for the area indicates that the plant species present could include Needle and Thread Needlegrass (*Hesperostipa comata*), Thurber's Needlegrass (*Achnatherum thurberianum*), Bottlebrush Squirreltail (*Elymus elymoides*), Basin Wildrye (*Leymus cinereus*), Wyoming Big Sagebrush (*Artemsia tridentata wyomingensis*), Mountain Big Sagebrush (*Artemsia tridentate vasayana*), Antelope Bitterbrush (*Purshia tridentata*), Douglas Rabbitbrush (*Chrysothamnus viscidiflorus*), Green Ephedra (*Ephedra viridis*), Anderson Peach Brush (*Prunus andersonii*), Spineless Horsebrush (*Tetradymia canescens*) and Phlox (*Phlox spp*.)

The Washoe County Nevada South Part soil survey for the area indicates that the soil types present are dominated by sandy loams, coarse sands, and loamy sands.

Experimental Design

The experimental area was fenced in April of 2004. Four treatments, three replicates of each, were applied in large (15 acre) plots. Treatments applied to investigate cheatgrass control include the

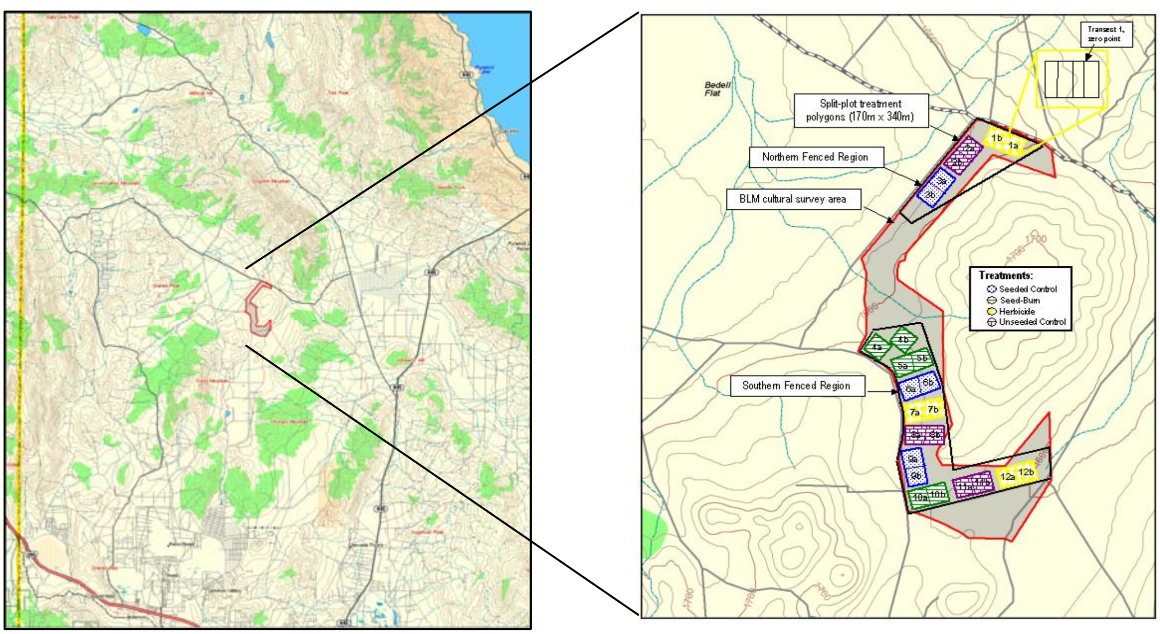


Fig. 10.1. The Bedell Flats Experimental Area.- T23N/R19E – Sections 24, 25, 26, 36, Located approximately twenty miles north of the city of Reno, Nevada.

following: (a) no pre-treatment but seeding of native species in fall 2005; (b) nurse crop (*Triticale* species) seeded in fall of 2004, prescribed burn in fall 2005, and seeding of native species in fall 2005 (after burn); (c) herbicide in spring 2005 and seeding of native species in fall 2005; and (d) no pre-treatment and no seeding treatment (*i.e.* control plots with natural regeneration of native vegetation after fencing). The treatment plots were split and seeded with one of 2 seeding mixtures: 1) the six accessions from Experiment 1 that were found to be most competitive with cheatgrass; and 2) the same seed mix used in the functional group approach (Experiment 2).

The restoration treatments were applied in a randomized block design consisting of three blocks. Each block consists of four split-plots with a buffer between each set of plots of at least 30m. Each individual plot was 170m x 170m with a 15m buffer between split-plots. To reduce edge effects, the sampling area was limited to an area of 150m x 150m at the center of each plot. Actual sampling occurred along three stratified random 150m transects set perpendicular to seeding rows.

Background Vegetation

Total background vegetation cover was estimated in June 2006 using the point-intercept method. Species were combined into functional groups (annual forbs, perennial forbs, bunchgrasses, shrubs, *Bromus tectorum*) and analysis of variance for split plot was run using the Analyst application of SAS PROC Mixed Models.

Density

Plant density counts were taken early in the growing season (late May) in 2006. Target (seeded) species as well as background species were counted in 1m x 50cm sampling frames with the 1m side running parallel to the transect (crossing 3 drill rows). All individuals falling within the sampling frame were counted. 3 replicate sampling frames were counted per transect. Permanent sampling locations were randomly stratified along each transect and locations were recorded. Species were combined into functional groups (annual forbs, perennial forbs, bunchgrasses, shrubs, *Bromus tectorum*) and analysis of variance for split plot was run using the Analyst application of SAS PROC Mixed Models.

Biomass

To evaluate the standing biomass, we sampled the Experiment 3 area twice in 2005 (treatment year) to determine pre (April) and post (June) treatment biomass. In 2006, we sampled once in mid-June to estimate maximum yearly biomass. Biomass samples were collected at two randomly selected locations along each of the three, permanent, 150-meter transects located within each subplot, using a 0.5 m X 1.0 m sampling frame. Biomass samples were always collected on the right side of the transect, in relation to the road. All aboveground vegetation was clipped at ground level. Samples were divided into two categories, “cheatgrass” and “other.” Biomass samples were then oven dried at 60° C for 48 hours, and weighed to determine dry biomass. “Other” samples were separated by species after oven dried, and dry weights were recorded for each species. Species were combined into functional groups (annual forbs, perennial forbs, bunchgrasses, shrubs, *Bromus tectorum*) and analysis of variance for split plot was run using the Analyst application of SAS PROC Mixed Models.

Soil Seedbank

To evaluate the seedbank, we sampled the Experiment 3 area once per year after seed drop (October 2005, September 2006) before first fall rains and to fall germination. In 2005, seedbank samples were taken before fall treatment seedings. We estimated the number of seeds, by species, present on the soil surface and in the top 2 cm of the soil profile. Each sample was separated into two portions: (1) litter and surface seeds and (2) 0-2 cm soil depth.

The sample areas were located within the sub-plots on the right side of each 150-meter vegetation transect belt, at 5 m distance from the transect. Sampling locations were determined by dividing each transect into four equal sections, and randomly selecting a location within each section. This design avoided sampling in or around the vegetation transects, as well as provided a sufficient, statistically representative sample of the entire 150 m X 150 m sub-plots. Permanent sampling locations were recorded. In addition, 6 samples were taken from each burn treatment sub-plot immediately following the prescribed burn in October. Sampling locations in consecutive years will be offset from the previous year by 0.5 meter.

Four composite samples were taken per transect, with each composite sample consisting of 4 soil cores (2" inside diameter PVC pipe) taken at each corner of a 30 x 30 cm sampling quadrat. Surface litter and seeds from each of the four subsamples were combined into one bag, and soil (0-2 cm depth) from each of the subsamples were mixed and bagged. All samples were stored in sealed plastic bags.

The seedbank was evaluated by direct germination in a greenhouse after wet-cold stratification. Samples were moistened approximate to field capacity (the point at which the soils are thoroughly moist without any standing or free water) and placed in cold storage (~ 1-2 °C) for 60 days. Litter samples were mixed with ~ 300 g of sterilized sand before being moistened. After stratification, each composite sample was spread over moistened sterilized sand in trays (to a depth of 1.0 cm), and watered to stimulate germination under natural light. Soil was kept moist throughout the entire period. As seedlings become identifiable they were identified, counted and removed. Unidentifiable seedlings were transplanted to pots and grown until they could be identified. When emergence was no longer observed, samples were allowed to dry for 30 days and then rewetted to test for further emergence.

Bromus tectorum was the only species with a large enough sample size on which to perform statistical analysis. Analysis of variance for split plot was run using the Analyst application of SAS PROC Mixed Models.

Soil Nutrients

An experimental design was instituted to evaluate the differences between soil nutrient availabililty following site preparation treatments (seed/burn, herbicide, unseeded control, seeded control). We chose resin capsules, spherical mesh-covered filled high capacity anion and cation exchangers, to gauge nutrient availability. Resin capsules integrate nutrient availability during the period they are in the soil via diffusion of anions and cations to the resin capsule. We feel that this integrative approach is superior to periodic destructive soil sampling. Moreover, resin capsules more closely approximate true plant availability albeit on a small scale. Resin capsule have great utility in quantifying nutrient availability of many nutrient for macro to micro. Resin capsules have been used to quantify availability of NO_3^-, K^+, Ca^{+2}, Mg^{+2}, Fe, Mn, Cu, and Zn. For statistical analysis, sample unit was an average of the samples for each block for each season. Data were analyzed using SAS PROC mixed models analysis of variance using a lognormal distribution for all analyses.

RESULTS

Because these data were collected just one year following ground preparation and seeding treatments, many of the significant results that we saw were a year effect, describing a difference between pre-treatment and post-treatment years. Additional sampling will be required before final treatment effects can be described.

Background Vegetation:

We sampled background vegetation using the point intercept method to describe the existing vegetation (in percent cover) across the study sites. Cheatgrass cover (**Fig. 10.2**) averaged from 21% in herbicide treated plots to 64% in plots that were

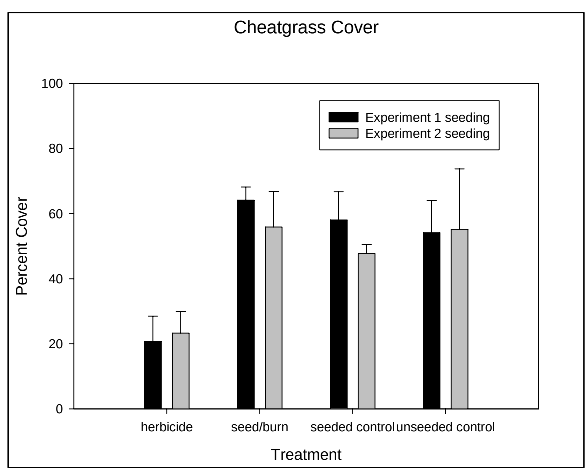
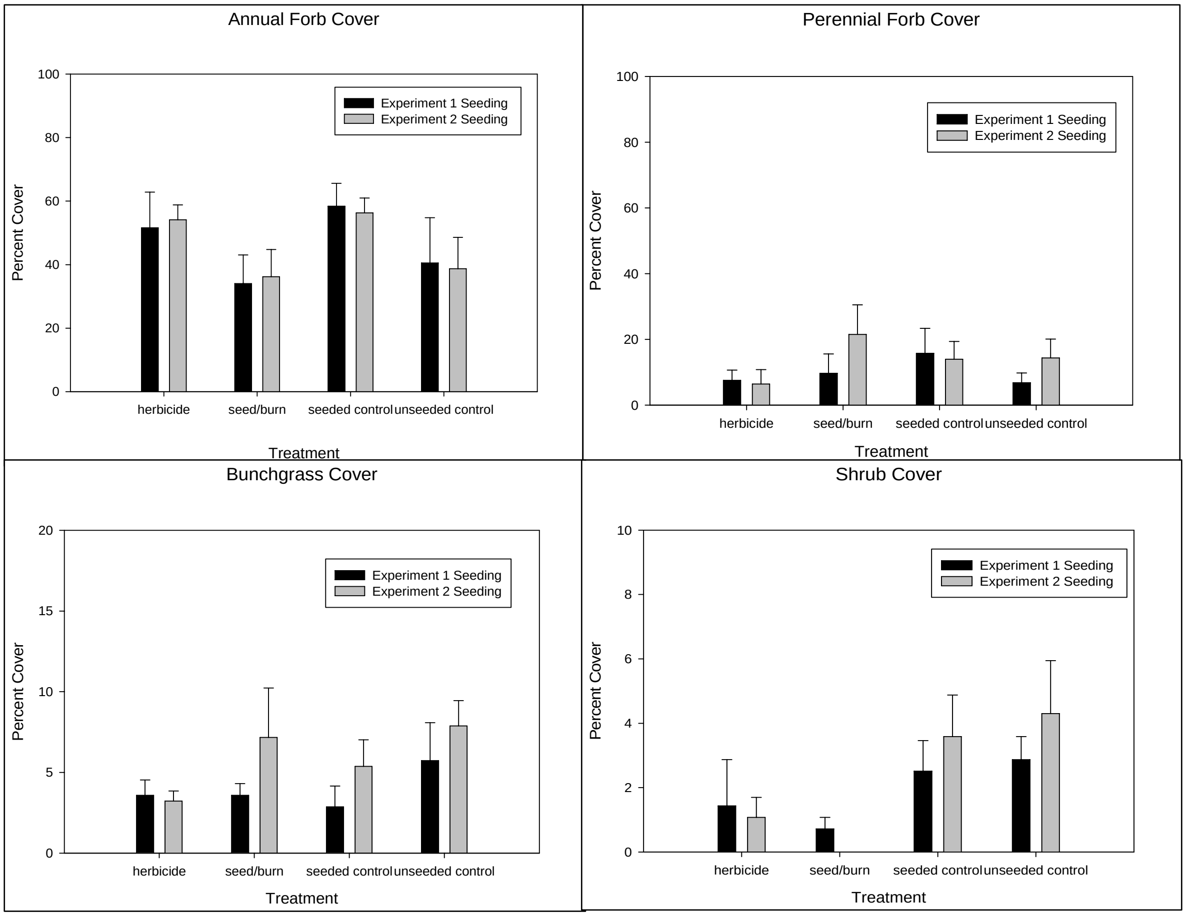


Fig. 10.2. There was no significant difference in cheatgrass percent cover between treatments (p=0.07).



Figs. 10.3-10.6. There was no significant difference in percent cover of annual forbs (p=0.22), perennial forbs (p=0.62), bunchgrasses (p=0.41), or shrubs (p=0.07) one year following site preparation treatments.

burned, although there is only a suggestion of a treatment effect (p=0.07) between site preparation treatments. There was no difference in cheatgrass cover between seeding treatments (p=0.32) or any interaction effect between site preparation and seeding treatments (p=0.51).

In the first post-treatment sampling year, we saw no treatment effects (**Figs. 10.3-10.6**; note different scales). Percent cover did not change for annual forbs (p=0.22), perennial forbs (p=0.62), bunchgrasses (p=0.41), or shrubs (0.07) following herbicide, burning, or seeding treatments.

Density

Cheatgrass density (**Fig. 10.7; Table 10.1**) was significantly lower (p=0.01) one year following seeding in the Experiment 2 seedings than in the Experiment 1 seedings. We saw no effect on cheatgrass density (p=0.22) due to ground preparation in the first year following treatment. The interaction of treatment by seeding treatment was not significant (p=0.20).

Planted species (target) density was inversely correlated with cheatgrass density. There were more

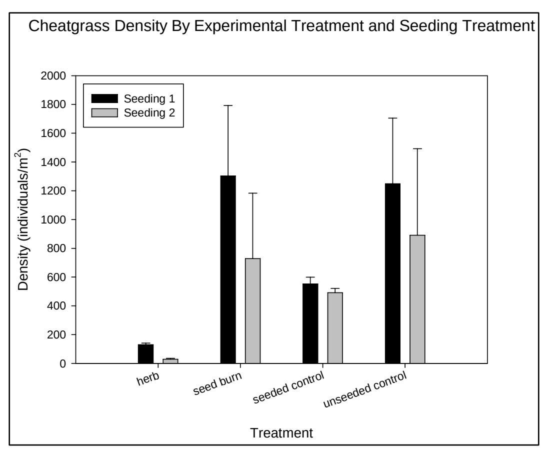


Fig. 10.7. There was no significant difference in cheatgrass density between treatments (p=0.22). Cheatgrass density was significantly lower (p=0.01) in Experiment 2 seedings than in Experiment 1 seedings.

germinants of planted species (**Fig. 10.8**) in Experiment 2 seedings, where we saw lowered cheatgrass density. Ground preparation treatment was significant (p=0.003), with more germinants of target species seen in plots which were treated with herbicide than in the burn or control plots. This trend was most pronounced in Experiment 1 seedings (p=0.08 for interaction term of ground treatment by experimental seeding).

One year following treatment, there was no difference in perennial bunchgrass density (**Fig. 10.9**) between either site preparation (p=0.17) or experimental seeding (p=0.11) treatments, nor was there any interaction effect (p=0.21). We saw no difference in response of either annual or perennial forbs following site preparation treatment (p=0.73 annual forbs; p= 0.30 perennial forbs) or seeding treatment (p=0.55 annual forbs; p=0.50 perennial forbs).

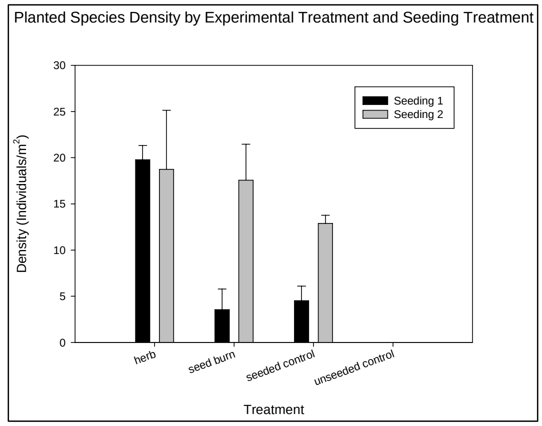


Fig. 10.8. We saw a significant difference in density of planted (target) species between ground preparation treatments (p=0.003). Planted species density was significantly lower (p=0.01) in Experiment 1 seedings than in Experiment 2 seedings. There is a suggestion of an interaction (p=0.08) between ground preparation treatment and experimental seeding).

Biomass

A significant (p=0.02) increase was seen in cheatgrass biomass (**Fig. 10.10**; **Table 10.2**) between sample years 2005 and 2006. There was no difference in biomass of cheatgrass due to either ground preparation (p=0.31) or experimental seeding (p=0.42) treatments.

Biomass of annual forbs (**Fig. 10.11**) significantly decreased (p=0.01) overall from 2005 to 2006. While neither site preparation (p=0.77) nor seeding treatment (p=0.58) was significant, there was a significant interaction (p=0.05) of year by site preparation treatment. This interaction term was significant largely due to higher biomass of annual forbs in the unseeded control the year following treatment (2006). Perennial forb biomass was not altered by treatment one year following treatment and seedings (ground preparation treatment, p=0.15; seeding

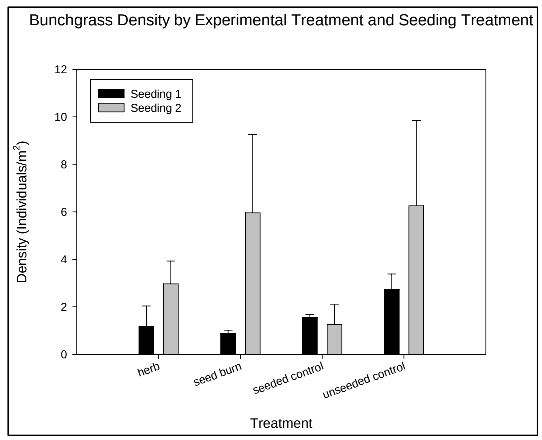


Fig. 10.9. There was no significant difference in bunchgrass density in response to either ground preparation treatment (p=0.17) or experimental seeding (p=0.11).

Table 10.1. Experiment 3 Density: Few treatment effects were seen in first post-treatment sampling year.

Experiment 3 Density 2006		*Bromus tectorum*		Target		bunchgrass		forb		shrub	
		mean	SE	mean	SE	mean	SE	mean	SE	mean	SE
Exp 1	herbicide	129.17	12.43	19.78	1.54	1.19	0.85	571.45	182.62	0.15	0.07
Exp 1	seed and burn	1302.43	489.85	3.56	2.23	0.89	0.13	320.74	77.84	0.15	0.15
Exp 1	seeded control	552.55	45.81	4.52	1.58	1.56	0.13	1003.93	521.81	0.67	0.44
Exp 1	unseeded control	1248.61	455.95	0.15	0.15	2.74	0.65	1129.95	776.41	0.07	0.07
Exp 2	herbicide	28.70	7.18	18.74	6.40	2.96	0.96	575.11	83.27	0.67	0.13
Exp 2	seed and burn	728.36	454.14	17.56	3.91	5.96	3.30	631.08	223.79	0.22	0.22
Exp 2	seeded control	491.55	29.37	12.89	0.89	1.26	0.82	713.01	168.97	0.59	0.07
Exp 2	unseeded control	889.81	602.40	1.93	1.00	6.25	3.59	648.65	329.73	0.67	0.67

Table 10.2. Experiment 3 Biomass

Experiment 3 Biomass 2006		*Bromus tectorum*				Target				bunchgrass			
		2005		2006		2005		2006		2005		2006	
		mean	SE	mean	SE	mean	SE	mean	SE	mean	SE	mean	SE
Exp 1	herbicide	10.32	1.93	18.81	7.95	0.00	0.00	0.04	0.04	14.08	3.48	11.26	3.31
Exp 1	seed and burn	24.27	3.57	26.17	1.09	0.00	0.00	0.09	0.05	3.04	0.46	10.60	5.21
Exp 1	seeded control	8.87	1.53	13.06	3.90	0.00	0.00	0.17	0.10	9.81	4.22	4.54	0.82
Exp 1	unseeded control	15.75	6.51	16.63	8.11	0.00	0.00	0.08	0.04	9.51	3.28	6.42	0.75
Exp 2	herbicide	12.90	3.99	18.30	1.48	0.00	0.00	0.09	0.02	1.73	1.51	13.41	5.51
Exp 2	seed and burn	14.23	4.13	18.99	3.67	0.00	0.00	0.04	0.03	8.35	2.89	10.41	7.94
Exp 2	seeded control	10.65	2.01	11.61	2.31	0.00	0.00	0.01	0.01	6.18	0.95	1.34	1.23
Exp 2	unseeded control	12.96	4.04	21.07	9.66	0.00	0.00	0.07	0.06	10.44	7.17	2.02	1.24

		annual forb				perennial forb			
		2005		2006		2005		2006	
		mean	SE	mean	SE	mean	SE	mean	SE
Exp 1	herbicide	21.55	13.75	17.01	6.88	20.59	14.99	30.07	7.53
Exp 1	seed and burn	41.70	3.37	29.64	6.32	16.19	7.38	22.53	5.28
Exp 1	seeded control	7.59	1.67	16.13	6.58	10.84	5.08	6.87	5.78
Exp 1	unseeded control	15.33	3.94	11.96	4.90	10.30	3.48	5.11	1.61
Exp 2	herbicide	14.83	7.27	4.16	2.54	21.87	14.40	34.67	10.38
Exp 2	seed and burn	9.18	6.24	3.93	2.88	17.44	4.92	33.53	12.98
Exp 2	seeded control	11.53	7.02	8.51	2.33	29.17	6.08	1.11	1.11
Exp 2	unseeded control	14.40	7.80	24.30	6.36	8.94	1.39	12.40	4.02

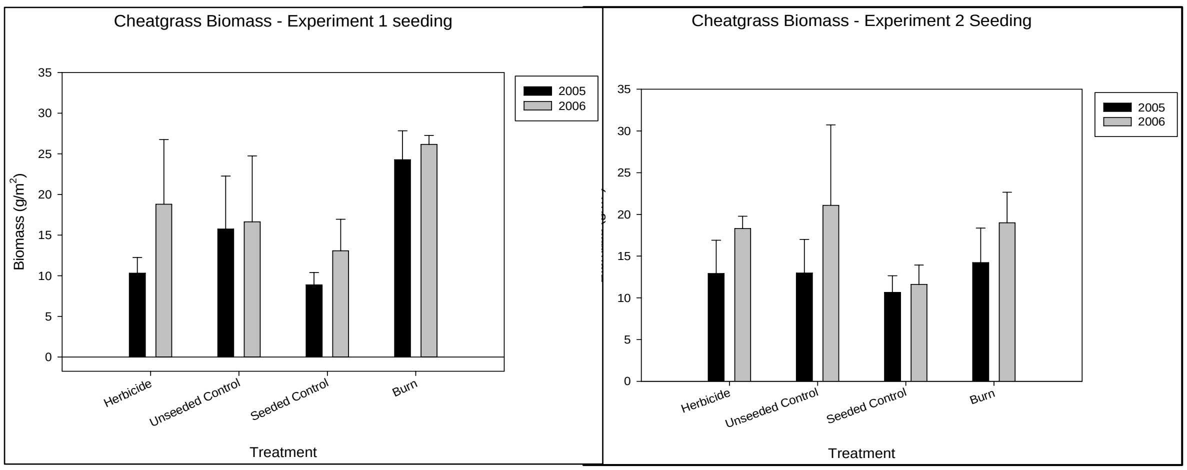


Fig. 10.10. Cheatgrass biomass was higher (p=0.02) following experimental treatments. There was no significant difference in cheatgrass biomass in response to either ground preparation treatment (p=0.31) or experimental seeding (p=0.42).

treatment, p=0.82; interaction, p=0.30).

Perennial bunchgrass biomass (**Fig. 10.12**) was not different between years (p=0.29) or site preparation treatment (p=0.29), but there is a suggestion of a difference between seeding treatments (p=0.06), with a decrease in biomass following treatment in experiment 1 seedings. The interaction of year by seeding treatment was statistically significant (p=0.02).

Soil Seedbank

In a greenhouse germination experiment, cheatgrass (**Fig. 10.13**) was the only species with a large enough sample size to analyze statistically. There was no significant difference in the soil seedbank as a result of treatment (p=0.07), but a trend towards lower numbers of cheatgrass germinants in herbicide plots than in burn or control plots. Seeds germinated from litter seedbank samples were significantly higher in pre-burn plots than in treatment or control plots (p=0.01), but we believe that this may be due to sampling error, as pre-treatment plots are not expected to be different from controls.

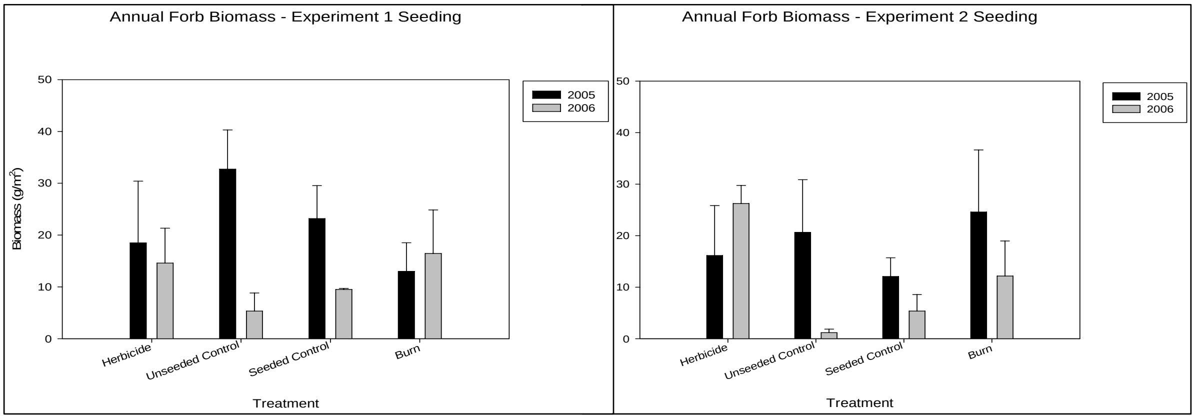


Fig. 10.11. Annual forb biomass was higher (p=0.01) following experimental treatments. There was no significant difference in annual forb biomass in response to either ground preparation treatment (p=0.77) or experimental seeding (p=0.58).

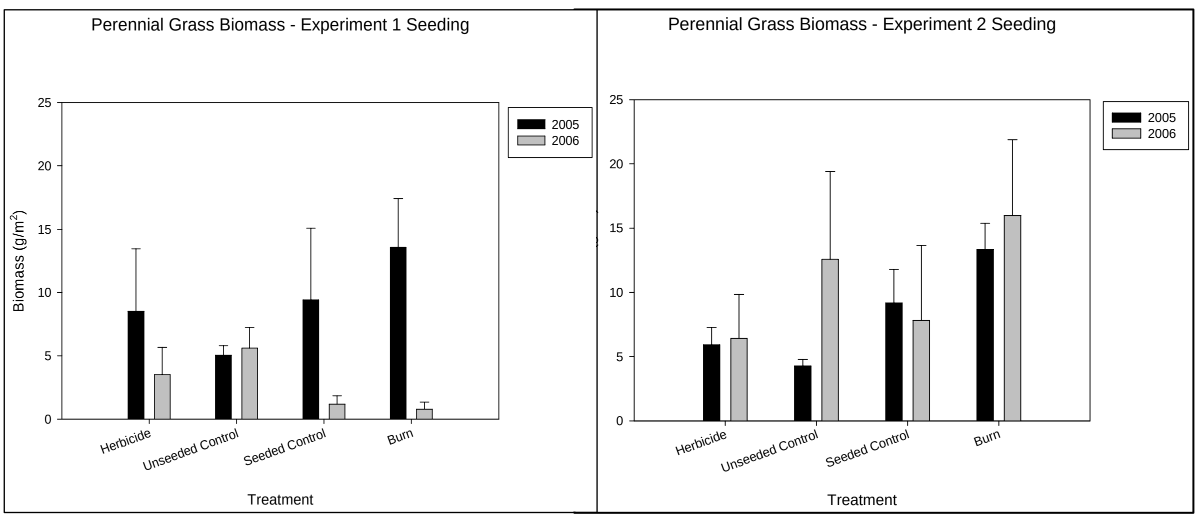


Fig. 10.12 Perennial bunchgrass biomass was not affected by year (p=0.29) or ground preparation treatment (0.29). There is a suggestion of a difference (p=0.06) between seeding treatments, with a decrease in biomass in some post treatment plots with experiment 1 seed mixtures. We saw a significant interaction (p=0.02) between year and experimental seeding).

Soil Nutrients

Soil nutrient availability (**Fig. 10.14**) was not affected by ground preparation treatments in the first post-treatment year (Mn, p=0.79; Fe, p=0.74; Ca, p=0.91; K, p=0.63; Mg, p=0.76; P, p=0.71; NH_4, p=0.92; NO_3, p=0.42). Sampling season (2/7/06-4/28/06 or 4/29/06-9/14/06) resulted in a significant increase in availability of Mn (p=0.001) and Fe (p<0.001) in later sampling season, a decrease in availability of NH_4 (p<0.001) in the later sampling season and no significant change in Ca (p=0.12), K (p=0.28), Mg (p=0.76), P (p=0.71), or NO_3 (p=0.07). The interaction of sampling season and treatment was not significant for any element.

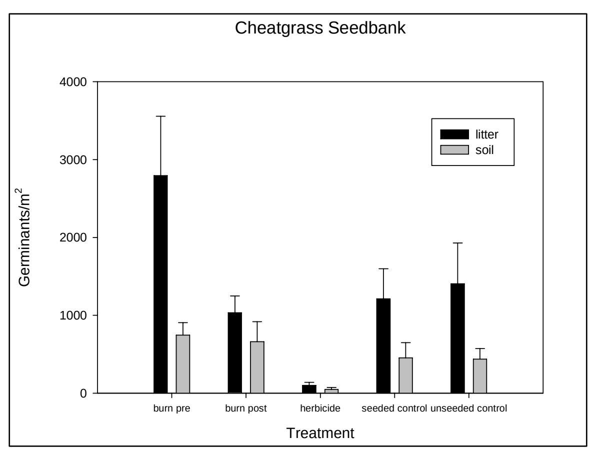
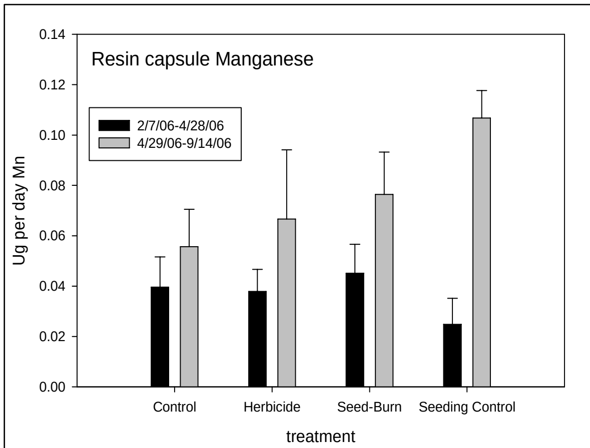


Fig. 10.13. Cheatgrass seedbank: There was a trend towards lower post-treatment germination in plots treated with herbicide (0.07).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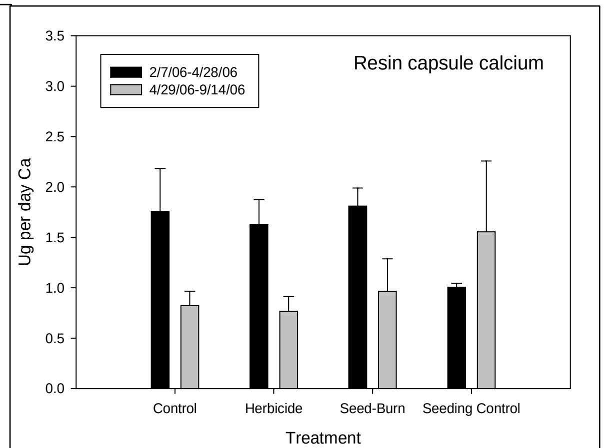
2/7/06-4/28/06
4/29/06-9/14/06
Ug per day Mn
Control
Herbicide
Seed-Burn
Seeding Control
treatment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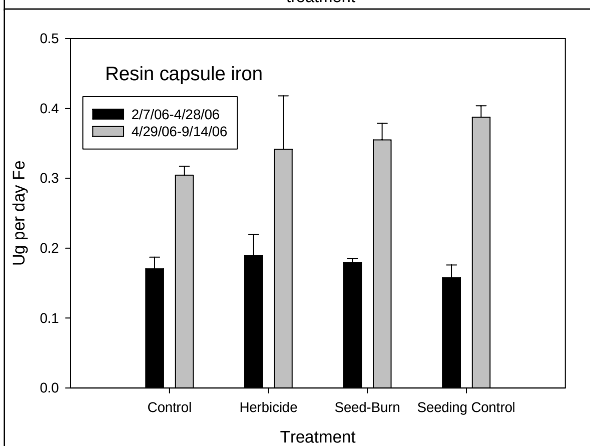
2/7/06-4/28/06
4/29/06-9/14/06
Ug per day Ca
Control
Herbicide
Seed-Burn
Seeding Control
Treatment


Resin capsule iron
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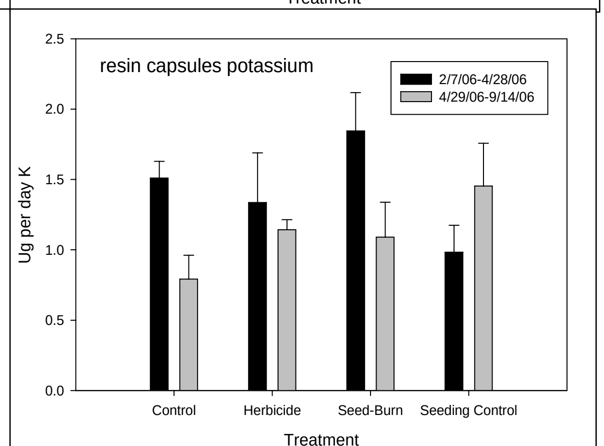
4/29/06-9/14/06
Ug per day Fe
Control
Herbicide
Seed-Burn
Seeding Control
Treatment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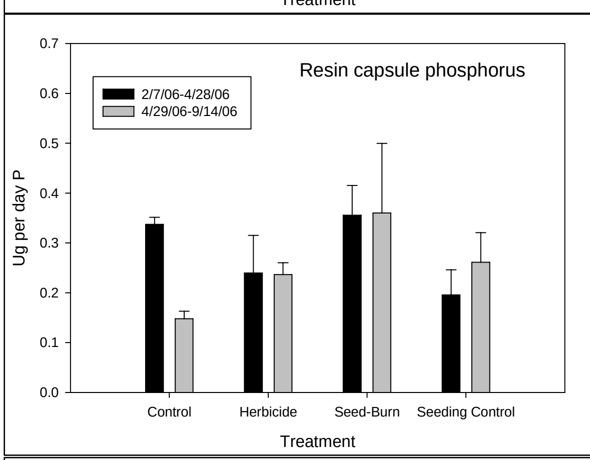
2/7/06-4/28/06
4/29/06-9/14/06
Ug per day K
Control
Herbicide
Seed-Burn
Seeding Control
Treatment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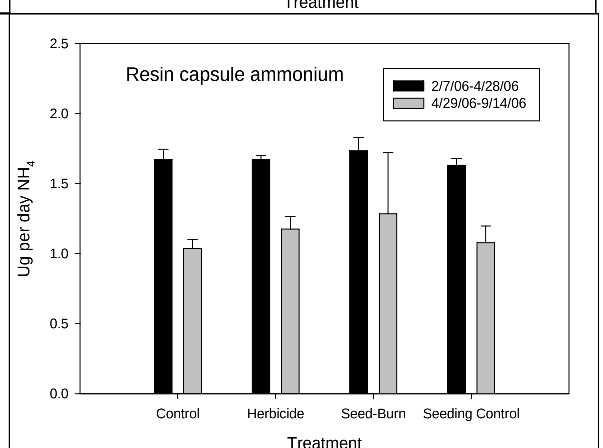
4/29/06-9/14/06
Ug per day P
Control
Herbicide
Seed-Burn
Seeding Control
Treatment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4/29/06-9/14/06
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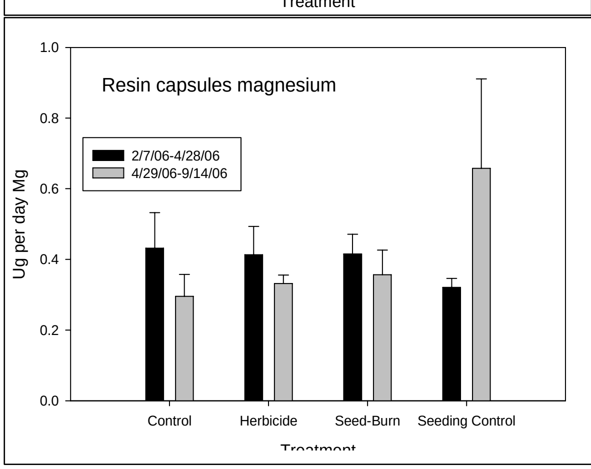
Control
Herbicide
Seed-Burn
Seeding Control
Treatment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Seed-Burn
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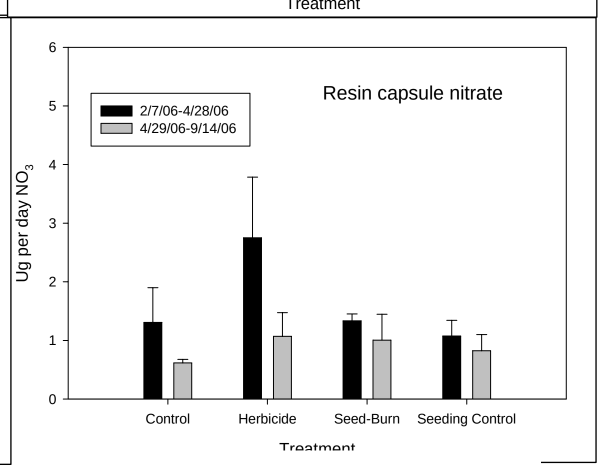
Resin capsule nitrate
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4/29/06-9/14/06
Ug per day NO_3
Control
Herbicide
Seed-Burn
Seeding Control

DISCUSSION AND FUTURE DIRECTION

The issue of restoration of the sagebrush biome is complicated by issues such as invasive species, cattle grazing, diminished native seed sources, and altered fire regimes. The current data sets represent a baseline by which we can begin to investigate the long term response of these areas following experimental treatments and native seedings. Continued monitoring will elucidate combinations of site preparation and seeding treatments which, in concert with the removal of livestock grazing, provide an effective method of decreasing cheatgrass dominance and restoring native vegetation communities.

Biomass, density, soil seedbank, and soil nutrient availability will be re-sampled in the coming years, with a final sampling scheduled for 2016, ten years following treatments.

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Chapter 11 – The net effect of granivory in the process of Great Basin desert ecological restoration

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INTRODUCTION

Granivorous animals are critical components within many ecosystems around the world (Brown et al. 1979, Davidson et al. 1980, Crawley 1983, Brown and Heske 1990, Crist and MacMahon 1994, MacMahon et al. 2000). Seed dispersal and seed predation by granivores are considered to be key processes affecting recruitment and survival of plants (Davidson 1977, Hansen 1978, Inouye et al. 1980, Schupp and Fuentes 1995, Brown et al. 1986, Gibson et al. 1990, Wilson et al. 1990, Howe and Brown 2001). North American deserts are home to a diverse and abundant assemblage of animals that have diets consisting largely of seeds (Hobbs 1985, Kelrick et al. 1986, Hölldobler and Wilson 1990, Smith 1990, Longland 1993, Kelt et al. 1996, Kelt and Brown 1999). Rodents, birds and ants, all of which can vary greatly in abundance both temporally and spatially, constitute the most important granivores in these systems (Brown et al. 1979, Parmenter et al. 1984, Price and Heinz 1984, Mull and MacMahon 1997). Despite much research on various ecological aspects of granivores, little work has been done with the primary focus linking granivory and vegetation management or restoration (Kelrick and MacMahon 1985).

The negative impacts of granivorous animals due to direct seed losses in revegetation efforts have been recognized for years (Smith and Aldous 1947, Spencer 1954, Tevis 1953, Abbott 1961, Howard and Cole 1967). At the same time, xeric rangelands have been promoted as a potentially good laboratory to explore the integration of granivory and vegetation management because seeds are an important food resource for granivores in such community types (Kelrick and MacMahon 1985, Brown et al 1986, Archer and Pyke 1991, Longland and Bateman 1998, Whisenant 1999, Longland et al. 2001). Chambers and MacMahon (1994) suggest that where natural densities of granivores are high, there is great potential for management of such animals to promote the establishment of desirable restoration species. What is lacking, however, is sufficient research with appropriate applications (Kelrick and MacMahon 1985).

Although many reports have assumed rodents negatively impact plant fitness through seed predation, more recent research demonstrates a positive role rodents can have in plant recruitment via seed caching activities (West 1968, McAdoo et al. 1983, McMurry et al. 1997, Vander Wall 1990, 1992, 1993, 1994, Longland et al. 2001, Theimer 2005). Specifically, seeds of some desert plants may have evolved to rely on rodents for dispersal via seed caching to microsites that are favorable for germination (Vander Wall 1990, Longland and Bateman 1998, Longland et al. 2001, Theimer 2005). Rodents may cache seeds either in a central location such as a burrow, called larderhoards, or in shallow holes covered with soil around the surface of their home ranges, called scatterhoards. Scatterhoards can contribute to seedling recruitment of certain plants, sometimes considerably. For example, Longland et al. (2001) showed that seedling recruitment of the native perennial bunchgrass, *Achnatherum hymenoides*, following initial caching by a single Merriam's kangaroo rat (*Dipodomys merriami*), was significantly greater than for seeds not harvested by granivores or than those harvested by ants. The implications of such mutualistic plant-animal interactions can have great significance for successful rangeland restoration.

The present research is centered on gaining a better understanding of the role of granivores in restoration/revegetation with special attention given seed removal (seed choice and rates of removal) and the effect cheatgrass has on ants and rodents as well as how site treatments and seeding influence rodent communities. Specifically, this research addressed three objectives: (1) Identify and determine relative abundances of granivore species (ants and rodents) in paired cheatgrass-dominated and reference sagebrush communities, (2) Determine seed removal rates of potential restoration species and the weed cheatgrass by rodents and ants, and whether the presence of cheatgrass affects harvesting of desirable species' seeds in field conditions, and (3) Determine rodent interactions with large-scale restoration efforts, including the effects of seedbed treatments on rodent communities and the effects of rodents on restoration via seed predation and/or seed caching behaviors.

METHODS

Study Sites

The experimental locations for this research were conducted at or near the IFAFS restoration sites in Utah, or at the IFAFS Bedell Flat restoration demonstration site (experiment 3) in western Nevada. To accomplish these objectives we are/have conducted several studies. Four studies are located in the Utah west desert of the eastern Great Basin and one within the western Great Basin in the state of Nevada.

Utah study sites

For the experiments conducted in Utah we established five sites on land owned and managed by the Bureau of Land Management (BLM) in Tooele County, Utah. Three sites are located near the Vernon Hills IFAFS site and the remaining two are located near the Simpson Spring IFAFS site. At each site a 1.5-ha sagebrush plot and nearby 1.5-ha cheatgrass plot were established, resulting in 10 distinct plots. Sagebrush plots were dominated by *Artemisia tridentata* (Big sagebrush), with such species as *Elymus elymoides* (bottlebrush squirreltail), *Achnatherum hymenoides* (Indian ricegrass), *Poa secunda* (Sandberg bluegrass), *Stipa* spp. (Needle grasses), *Bromus tectorum* (cheatgrass), *Atriplex* spp. (Saltbrush), *Ephedra* spp. (Mormon tea), and others also present. Cheatgrass-dominated plots were dominated by *Bromus tectorum,* but also had other mixed weedy species and the occasional native perennial grass.

Nevada study site

Our research is being conducted in northwestern Nevada on a BLM allotment near Bedell Flat (39°49'36"N, 119°48' 25"W), approximately 37 km NE of Reno, Washoe County, Nevada. In 2000, approximately 1,400 ha of Great Basin sagebrush-steppe burned and was subsequently seeded with a mix of Critina thickspike wheatgrass (*Agropyron dasystachyum*), Hycrest crested wheatgrass (*A. cristatum*), Arriba western wheatgrass (*A. smithii*), four-wing saltbrush (*Atriplex canescens*) and Ladak alfalfa (*Medicago sativa*). Seeding was generally unsuccessful and *B. tectorum* was the most abundant species when this study was initiated in October 2005. A subset (174.42 ha) of the area that burned in 2000 is currently the site for a multi-agency/university restoration project where several experiments are being conducted in an attempt to understand interactions between disturbed habitats, vegetation restoration attempts and desert granivores. This site includes twelve 5.78 ha (*i.e.*, 170- x 340-m) plots which were fenced within two sections during April 2004 to restrict use.

Ant and Rodent Community Evaluation

In Utah the seed harvesting ant community was sampled with pit-fall trapping/collection methods. In both Utah (Vernon Hill and Simpson Springs) and Nevada the small mammal community was evaluated according to protocols outlined below.

Ant community inventory - Utah

Ant pitfall traps are 12-ounce tin cans baited with cookies and peanut butter and filled with 15% standard automobile antifreeze to approximately 3 cm. Traps were placed at 25 locations within each site. Traps were set for a period of two days in June 2005. Trapping of ants and rodents was not done concurrently in a plot. Ants collected in the traps were temporarily preserved in 70% isopropyl alcohol until laboratory identification to species occured. Verification of ant identifications is currently being conducted by Eli Sarnat in the Department of Entomology at the University of California at Davis. The data for this survey are not yet fully available, but a preliminary/working species list has been created and is shown in the results section below.

Rodent community inventory - Utah

Rodent communities were and are continuing to be sampled using Sherman live traps on a trapping grid. Traps are placed in a 10 x 10 trap grid arrangement with 10 m between adjacent traps (n = 100 traps/plot). Trapping is conducted for three consecutive nights in all cases and traps are checked and re-set each day. All animals trapped were field identified to species using standard morphological characteristics, weighed, sexed, marked, and released at the point of capture. Each plot was trapped 4 times between 2004/2005. Traps were baited with a combination of peanut butter and mixed bird seed.

Effect of Seedbed Treatments and Seeding on Rodent Communities- Nevada

Rodent live trapping using Shearman traps occured/will occur in, May, August, and October/November 2005, 2006, 2007, and 2008. During each trapping event 50-trap grids are established at 12 areas, one on each of the three replicates for each of the four treatments. Trapping events occur for a period of three consecutive nights. All animals trapped are field identified to species using standard morphological characteristics, weighed, sexed, tagged for individual identification and released.

Rodent and Ant Data and Analysis – Utah/Nevada

Rodent trapping data will be analyzed using the program MARK (White and Burnham 1999). This will allow us to estimate species densities and potentially migration. Rodent species densities will be compared between plots and between sites using one-way ANOVA’s and Chi square analyses. Specific characteristics to be considered within rodent analyses may include but would not be limited to; season, moonlight, seed pool/bank results, vegetation physiognomy, and/or ant community results. I will calculate rodent diversity, species richness, and species evenness (Alatalo's index). Because various diversity indices weight rare species differently I will use the series of diversity numbers ("Hill's Series") as measure of alpha and beta diversity which will provide a composite of diversity variations among the sites. The ant community data, including species richness, evenness (Alatalo’s index) and diversity will be analyzed with one-way ANOVA’s between plots and sites

Seed Removal Experiments for Ants and Rodents

We have conducted three closely related experiments with both seed eating rodents and ants to assess seed preferences for each group. We were specifically interested in rankings of seed preferences and in whether the presence of cheatgrass alters seed preference rankings and consumption by each group respectively.

Rodent seed removal - Utah

For this experiment we used 13 unique seed combinations. Seeds of five native grass species and of *Panicum miliaceum* (millet) were presented for removal individually or in mixture with *B. tectorum*; in addition, *B. tectorum* was available alone. The five native seed species were *Pseudoroegneria spicata* (bluebunch wheatgrass), *Elymus elymoides* (bottlebrush squirreltail), *Achnatherum hymenoides* (Indian ricegrass), *Poa secunda* (Sandberg bluegrass), and *Leymus cinereus* (Great Basin wildrye). These native seed species were selected because they are often used for reseeding/restoration projects in this region, few studies have used these seed species in this context, and they are common native species to the west desert region of central Utah. The weed species, cheatgrass (*B. tectorum*), was selected because it is locally common and/or widespread, it is thought to alter ecosystem processes (*e.g.* soil morphology or animal and/or plant diversity, physical cycles), and it may influence target seed choice by granivores. Millet (*Panicum miliaceum*) is included because it has been used extensively in seed selection experiments (Longland and Bateman 1998) and has been tested with some native species as a potential decoy seed in reseeding projects (Longland and Bateman 1998). In addition, the results of seed preference for millet versus other desirable seed species (*e.g.* Indian ricegrass) are inconclusive and/or choice varies as a function of seed predator type or is specific to the community where research was conducted (see Kelrick et al. 1986, Longland and Bateman 1998).

In each plot three, 3-g seed packets for each of the 13 seed combinations were placed in Petri dishes evenly located along 6 parallel 150-m transects positioned at a minimum of 20 m apart in both cheatgrass and sagebrush plots. Three transects had 6 dishes and the remaining three had 7 dishes. This results in 39 dishes per plot per sampling session (*i.e.*, 13 seed combinations, each replicated three times/night). Seeds that were presented alone (without cheatgrass) were in dishes containing three grams of that respective species. Seeds presented in mixture with cheatgrass were in dishes containing 1.5 g of one of the native species or millet and 1.5 g of cheatgrass. When quantifying rodent removal of seeds, dishes were available for one night (sunset to just before dawn). There were 24 replications in each vegetation type randomly distributed among the five plots.

Rodent seed removal using a fully factorial design (mixed densities experiment) - Utah

We used a factorial combination of varying densities of target and cheatgrass seed mixtures to test the simultaneous effects of overall seed densities and relative proportions of cheatgrass and target seed on removal. The target seed species were *Pseudoroegneia spicata* (Bluebunch wheatgrass), *Achnatherum hymenoides* (Indian ricegrass), and *Leymus cinereus* (Basin wildrye). The fully crossed densities of seeds were 0, 1, 2, 3, 4, and 5 g of target seeds mixed with 0, 1, 2, 3, 4, and 5 g of cheatgrass seeds, resulting in 35 combinations for each of the three target species (excluding the 0,0 combination).

Seed mixtures were placed in rodent-specific seed trays for a period of one night in seven 1.5-ha sagebrush plots. Each target species – cheatgrass seed combination was replicated 15 times in 2005 between the months of May – August. At the end of each trial seed trays were removed and seeds were separated by species, weighed and recorded.

Ant seed removal rates

The same 13 seed combinations used in the first rodent experiment above were used for the ant seed removal experiment. This seed removal experiment was conducted in the paired cheatgrass and sagebrush plots at the Vernon Hill location only. A seven day plastic pill box (28 x 3 x 5.5 cm) with internal dimensions of 5.2 x 4 x 2.3 cm/compartment was used to offer the seeds. Two holes (10 mm diameter) were drilled on opposite sides at 5 mm from the bottom into each individual compartment to allow ant access to seeds within. Monospecific treatments and mixture treatments were done concurrently in the same plot during any single trial period. Seeds were either offered in monospecific treatments, with all 7 of the seed types presented alone, randomly assigned to one of 7 locations within the 7 day pill box, or in mixture, where each of 6 target seeds were in mixture with cheatgrass seeds. Seeds that were presented alone (without cheatgrass) were in 2 g quantities. Mixture treatments consisted of 1 g of any one of the target seeds combined with 1 g of cheatgrass seeds. When one of the treatment types was selected for a trial, three replicates/distance from mound were done. These ant-exclusive seed dishes were placed at 4 locations from a pre determined active *Pogonomyrmex occidentalis* (Western harvester ant) mound. These distances from the mounds were: (1) at the internal edge of the mound clearing (but not at a distance greater than 1 m from the central mound, (2) 1 m from the mound clearing, (3) 3 m from the mound clearing, and (4) ≥ 5m from the nearest active mound. During any given trial period seeds were available for removal for a 48 period. Each treatment (monospecific or mixture)/location (cheatgrass or sagebrush)/distance was replicated 6 times in 2005. At the completion of any trial the seeds were removed from the tray, separated, reweighed and recorded.

An Evaluation of the Affect of Rodents on Reseeding - Nevada

Experiment 3 (restoration strategies) of the IFAFS restoration project has been developed to be an extension of both experiment 1 (plant material seeding trials) and experiment 2 (competitive interactions) of this initiative. The restoration strategies experiment investigates the effectiveness of 4 different restoration treatments and tests the ability of two carefully chosen seed mixtures to establish where *B. tectorum* dominates. Four restoration techniques, (prescribed fire, herbicide, seeded control, and no seed control) are targeted at reducing the cheatgrass seed bank. The four pre-seeding restoration treatments were applied in a randomized block design with three blocks. Each block consisted of four split-plots with a buffer between each set of split-plots of at least 30m. Each individual plot (*i.e.* half of one split-plot) is 170m x 170m with a 15m buffer at its edge. In November 2005, seeds were drilled into the pretreated sites.

Evaluation of Granivory on Reseeding

The experimental design for evaluating the influence of rodent granivory on this seeding effort will be a split-split-plot design with four treatment plots, each occurring once per seeding split-plot as outlined above (3 replications per restoration treatment). The five treatments for rodent granivory are: (1) closed to rodent granivores using fencing materials, (2) open to rodent granivores using fencing materials with entry holes cut at the base, (3) plot fenced for rodent caching with future access to rodents, (4) plot fenced for rodent caching with no future access to rodents and (5) open, with no fence material used in order to test the influence of the fence (treatment two) on rodent granivory. Treatments three and four allowed one *Dipodomys* spp. individual to harvest and potentially cache previously drill-seeded seeds for a 24-h period similar to the protocol used by Longland et al. (2001). This design will allow us to evaluate each end of the rodent granivory continuum on this reseeding effort; seed predation at the negative end to the best case scenario of seed dispersal via rodent seed caching of previously drill-seeded seeds.

Each plot other than treatment five was constructed of 5-m lengths of 10-wire "hog panel" fencing covered with ¼ inch hardware cloth and a 10-ininch strip of sheet aluminum flashing at the top to prevent rodents from climbing over the fence. Each plot was 5 x 5 x 1m tall and buried 30 cm to discourage rodent digging. For each plot, we will record numbers of seedlings of each restoration plant species that emerge in clumps from rodent scatterhoards and numbers that emerge singly. Although single seedlings may or may not have originated from a rodent cache, clumped seedlings can be assigned unambiguously to rodent caching activities. ANOVAs will be used to contrast species-specific seedling recruitment among different combinations of seeding treatments, rodent treatments (inclusion, exclusion, preliminary caching by a single rodent).

RESULTS

Ant Community - Utah

Ants collected in pitfall traps in the paired cheatgrass and sagebrush sites from Utah are currently being identified at the Department of Entomology at the University of California at Davis. We are therefore not able to report definitive results for this part of our research. However, Preliminary findings for the species positively identified to date are shown in **Table 11.1**.

Rodent Community – Utah

The results for the rodent community are shown in **Table 11.2**. We captured 8 species of small mammals. Note the marked differences in the numbers of individuals captured in the sagebrush plots compared to the cheatgrass plots. These results suggest a reduction in habitat suitability for these animals when sagebrush steppe is converted to cheatgrass-dominated mixed weedy annual grassland.

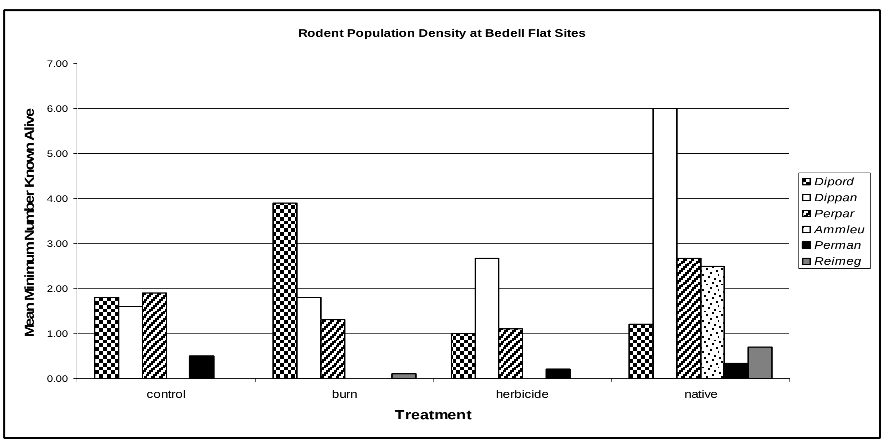

Fig. 11.1. Minimum numbers of animals by species that are known to occur on three of the treatment plots and in the two native vegetation plots. The grazing grids were eliminated from this data set as the grazing treatment was not done. The species and their corresponding codes are: *Dipodomys ordii* (Dipord), *D. panamintinus* (Dippan), *Peroganathus parvus* (Perpar), *Ammospermophilus leucurus* (Ammleu), *Peromyscus* maniculatus (Perman), and *Reithrodontomys megalotis* (Reimeg).

Influence of Restoration Treatments on the Rodent Community – Nevada

Trapping for small mammals at the Bedell Flat restoration site indicates that six species occur at or adjacent to the site. Recall trapping grids are located on each of 12 plots and in two plots directly adjacent to the restoration site that were not affected by the 2000 fire. Because we are planning to trap for 2-4 additional years the results reported in **Fig. 11.1** are preliminary.

Table 11.1. Shown is the species list for all ants captured which have been positively identified to date. *denoted a scientifically un-described species.

Genus	Species
Aphaenogaster	*unita*
Camponotus	*vicinus*
Forelius	*pruinosus*
Formica	*manni*
Formica	*sp.*
Monomorium	*ergatogyna*
Myrmecocystus	*testaceus*
Myrmecocystus	*hammettensis*
Myrmica	*tahoensis*
Pheidole	*pilifera*
Pheidole	*sp.*
Pheidole	*creightoni*
Pogonomyrmex	*occidentalis*
Solenopsis	*molesta*
Temnothorax	*rugatulus*
Temnothorax	*sp. CA-10**
Temnothorax	*nevadensis*

Table 11.2. The minimum number of animals known to occur in either the cheatgrass or sagebrush plots. The species scientific names and codes are: *Onychomys leucogaster* (Onyleu), *Dipodomys ordii* (Dipord), *Peromyscus maniculatus* (Perman), *Perognathus parvus* (Perpar), *Lemmiscus curtatus* (Lemcur), *Reithrodontomys megalotis* (Reimeg), *Peromyscus trueii* (Pertru), and *Ammospermophilus leucurus* (Ammleu).

	Rodent Species Captured							
Habitat	Onyleu	Dipord	Perman	Perpar	Lemcur	Reimeg	Pertru	Ammleu
Cheatgrass	0	14	35	7	4	2	0	0
Sagebrush	3	68	270	61	12	16	2	4

Ant Seed Removal – Utah

The ant seed removal data are not yet prepared for reporting.

Rodent Seed Removal - Utah

Preliminary results indicate there is a marked difference in the amount of seed removed between the two habitat types (*i.e.* cheatgrass and sagebrush). Moreover, significantly more seed was removed from the sagebrush plots than from the cheatgrass plots (see **Table 11.3**), as expected from the differences in rodent communities noted above. Additionally, we were able to detect a marked preference (*i.e.* ranking order) based on total seeds removed by species among the seven seeds when presented alone (without cheatgrass in the mixture) (see **Fig. 11.2**). The ranking order in the sagebrush plots only is: *Achnatherum hymenoides* (Indian ricegrass), *Panicum miliaceum* (millet), *Pseudoroegneria spicata* (bluebunch wheatgrass), *Elymus elymoides* (bottle bunch squirreltail), *Leymus cinereous* (Basin wildrye), *Poa secunda* (Sandberg bluegrass), and *Bromus tectorum* (cheatgrass). Preliminary results indicate that the ranking order shifts when the seeds are presented in the mixture treatments with cheatgrass. However these results are not yet ready to report as we are currently constructing the statistical model for that subset of the data (see **Fig. 11.2** for preliminary results).

Table 11.3. ANOVA results for fixed effects for seed removed in the sagebrush and cheatgrass plots when presented alone (without cheatgrass in the mixture).

Test for Fixed Effects – Monospecific Treatments Only			
Effect	**DF**	**F Value**	**P Value**
Seed	6,48	11.13	<.0001
Site Type	1,8	70.13	<.0001
Site Type*Seed	6,48	3.83	0.0034

Rodent Seed Removal Using a Factorial Design – Utah

Target seed harvest

The weight of target seeds removed increased as the initial density of target seed increased (df=1,43, P<.001) and decreased slightly as the initial density of *B. tectorum* increased (df=1,43, P=.016) (**Fig. 11.1**). There was no evidence that these patterns differed among target species (df=2,1209, P=.149) (**Table 11.4b**). Apparent differences in contour figures (see **Fig. 11.3**) for target species reflect the effect of statistically insignificant interactions. Each individual isocline line indicates an associated level of seed harvest for a respective target seed at all density combinations. **Fig. 11.3** indicates that increasing initial seed availability results in increased seed harvesting, as shown by the shifting of isocline harvest lines horizontally. The slope of the isocline lines shows the influence *B. tectorum* (x axis) had on the harvest of a target species. In general however, rodents tended to remove most target seeds, but particularly favored *P. spicata* over *L. cinereus*, over *A. hymenoides*. Target seed harvest was negatively influenced by the initial amount of *B. tectorum* seed present in the respective seed combination treatment (df=1,43, P=.016); and again this trend did not differ among the targets (df=2,43, P=.965) (see **Table 11.4b**).

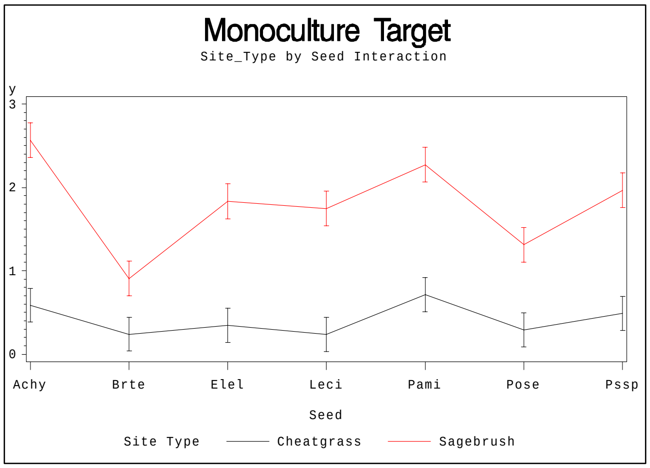

Fig. 11.2. Mean amount of seed removed by rodent for all seven seed species when presented without cheatgrass in the mixture for the sagebrush and cheatgrass plots.

Although target seed harvest did not appear to be influenced by the amount of *B. tectorum* seed in the mixture treatments (**Table 11.5**), the results displayed on the isocline plots for target seed harvest indicate the occurrence of a slight associational resistance of *B. tectorum* on the target seeds (see **Fig. 11.3**). The lack of slope and associated curvature indicates that *B. tectorum* had only marginal influence on the harvest of any target seed. For all three targets slightly less target seed was harvested with increasingly greater densities of *B. tectorum* seed present in the mixtures (shown by positive sloping lines in **Fig. 11.3**). However, at greater seed densities for *P. spicata*, less of that seed is harvested at greater (4 and 5 g) *B. tectorum* seed densities (df=1,396, P=.058) (see **Table 11.5** and **Fig. 11.3**).

***Bromus tectorum* seed harvest**

Like the three target seed species, harvest of *B. tectorum* also showed a density-dependent effect (**Fig. 11.4** and **Table 11.6**). The weight of *B. tectorum* seeds removed increased as the initial density of *B. tectorum* seed increased (df=1,42, P<.001); the magnitude of the increase was greater at higher initial target seed densities (df=1,43, P<.001) (**Table 11.4a**) and was most pronounced for *L. cinereus* (df=2,1195, P=.042). The amount of target seed initially available also had a significant positive effect on *B. tectorum* seed removal by the rodents (df=1,44, P<.001). The weight of *B. tectorum* seeds removed increased as the initial density of target seed increased; the magnitude of the increase was greater at higher initial *B. tectorum* densities (df=1,1195, P<.001) and was particularly pronounced for *L. cinereus* (df=2,1195, P=.042) (**Table 11.4a**). Furthermore, there was a species effect on *B. tectorum* seed removal (df=2,44, P=.012); that is, all *B. tectorum*/target seed combinations were not perceived in the same way by the rodents. In general, more *B. tectorum* seed was removed when in combination with *L. cinereus* and *P. spicata*, and less when in combination with *A. hymenoides* (see **Fig. 11.3**).

Table 11.4 a and b. MIXED procedure regression results for weight of *B. tectorum* seeds harvested (**Table 11.4a**) and the weight of target seed harvested (**Table 11.4b**) as a function of varying *B. tectorum* and target seed densities

a. *Bromus tectorum* seed harvested			
Effect	**DF**	**F-value**	**P-value**
Target species	2,43	1.99	.149
Target density	1,44	63.86	<.001
Target density*target species	2,44	4.85	.013
B. tectorum density	1, 42	107.62	<.001
B. tectorum density*target species	2, 42	0.56	.577
Target density**B. tectorum* density	1,1195	9.75	.002
Target density**B. tectorum* density*target species	2,1195	3.17	.043
b. Target seed harvested			
Effect	**DF**	**F-value**	**P-value**
Target species	2,43	0.19	.829
Target density	1,43	626.14	<.001
Target density*target species	2,43	0.02	.983
B. tectorum density	1,43	6.29	.016
B. tectorum start*species	2,43	0.04	.965
Target density**B. tectorum* density	1,1209	0.10	.754
Target density**B. tectorum* density* target species	2,1209	1.90	.149

The initial seed density of the targets also appeared to influence the amount of *B. tectorum* seed that was harvested by the rodents (see **Fig. 11.4**). The harvest of *B. tectorum* was marginally facilitated by the presence of the target species seeds in mixture. That is more *B. tectorum* seeds were harvested when they were in mixture with the target seeds (*i.e.* associational susceptibility or short-term apparent competition sensu Veech 2000, 2001). However, the only statistically significant pattern of associational susceptibility occurred for *L. cinereus* (df=1,393, P=.0004). More *B. tectorum* seed was harvested at increasingly greater seed densities of *L. cinereus* seeds, shown in the curvature of the isocline lines, which is suggestive of increased target harvest rates (see **Fig. 11.4**), this occurrence was less strong for *B. tectorum* harvest when present with *P. spicata* (df=1,392, P=0.13).

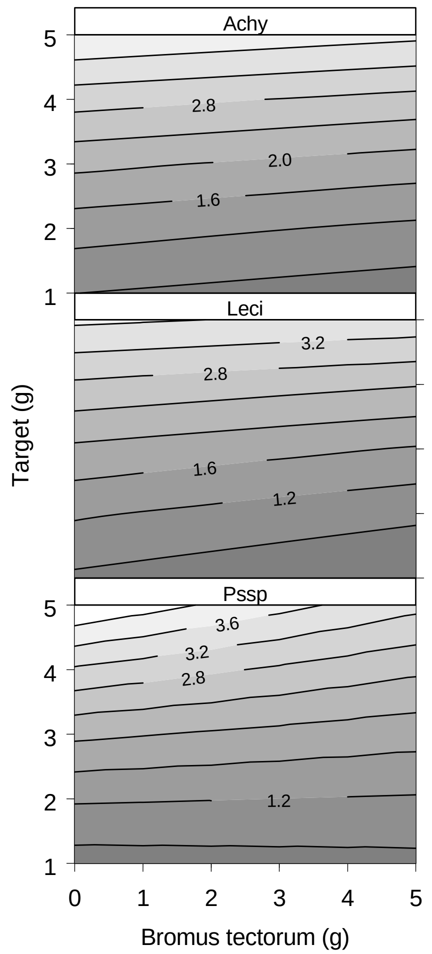

Fig. 11.3. Target seed removed for each of the three target seeds; *A. hymenoides*, *L. cinereus*, and *P. spicata* as a function of varying initial *B. tectorum* seed density. These topographical isocline contour plots depict changes in the amount of seed removed or harvested for each of the three targets at fixed start seed density of *B. tectorum*.

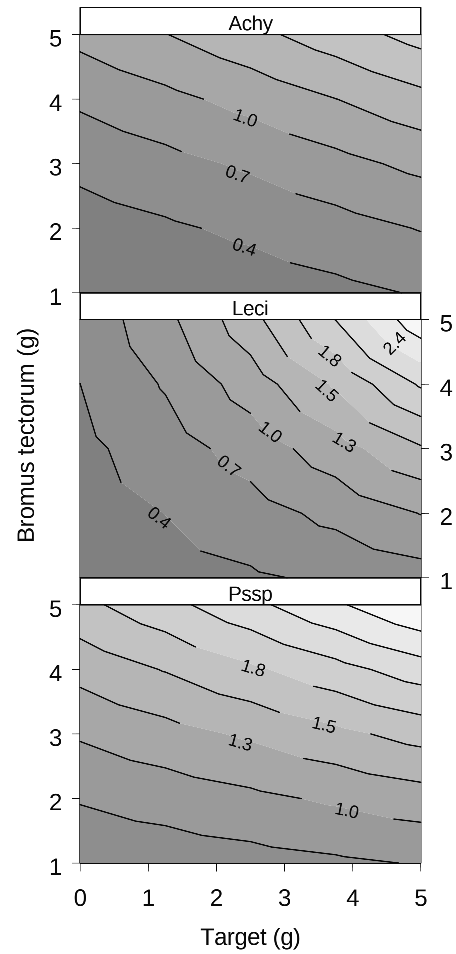

Fig. 11.4. *B. tectorum* seed removed for each of the three target seed mixture treatments. These topographical isoclines contour plots depict predicted changes in the amount of *B. tectorum* seed removed at varying seed densities for any given target.

Table 11.5. Results from the MIXED procedure for individual target seed harvested by species as a function of *B. tectorum* seed in mixture as well as target density.

Individual target seed harvested as a function of *B. tectorum* seed in mixture			
Effect	**DF**	**F-value**	**P-value**
***Leymus cinereus* seed harvest**			
L. cinereus density	1,14	164.67	<.001
B. tectorum density	1,14	2.16	.164
L. cinereus density**B. tectorum* density	1,399	0.67	.413
***Achnatherum hymenoides* seed harvest**			
A. hymenoides density	1,15	273.48	<.001
B. tectorum density	1,15	2.56	.129
A. hymenoides density**B. tectorum* density	1,415	0.100	.755
***Pseudoroegneria spicata* seed harvest**			
P. spicata density	1,13	215.66	<.001
B. tectorum density	1,13	1.79	.203
P. spicata density**B. tectorum* density	1,396	3.61	.058

Table 11.6. Results from the MIXED procedure of *Bromus tectorum* seed harvested as a function of each of the three specific target seeds in mixture and *Bromus tectorum* density.

Bromus tectorum **seed harvested as a function of each specific target seed**			
Effect	**DF**	**F-value**	**P-value**
Bromus tectorum **harvested when present with** ***Leymus cinereus***			
L. cinereus density	1,14	41.50	<.001
B. tectorum density	1,13	34.26	<.001
B. tectorum density**L. cinereus* density	1,393	12.61	.004
Bromus tectorum **harvested when present with** ***Achnatherum hymenoides***			
A. hymenoides density	1,15	15.87	.001
B. tectorum density	1,15	36.48	<.001
B. tectorum density**A. hymenoides* density	1,409	0.12	.734
Bromus tectorum **harvested when present with** ***Pseudoroegneria spicata***			
P. spicata density	1,14	9.72	.007
B. tectorum density	1,13	37.87	<.001
B. tectorum density**P. spicata* density	1,392	2.25	.134

Effect of Rodents on Restoration – Nevada

We do not yet have ample data to report on this experiment. As outlined above we intend to sample the response of vegetation from granivory and associated rodent activities annually through 2008.

SUMMARY

As a subdiscipline of ecology, restoration ecology is one that, under ideal conditions, integrates theory and application (Jordon et al. 1987). Research that explores the effects of animals on plant establishment fits well within the framework of restoration ecology, because directing plant community development requires the integration of ecological theory with management applications. Land managers and ecologists will need technology integrated with appropriate resources as well as a sound understanding of landscape and ecosystem-level processes (*e.g.* seed predation and/or dispersal) to find success in Great Basin rangeland restoration and revegetation (Archer and Pyke 1991, MacMahon and Kelrick 1985, Jordan et al. 1987, MacMahon 1997). It is possible that reclamation, restoration, and/or revegetation efforts could be enhanced if techniques are understood for managing revegetation efforts to minimize the impacts of seed predators and/or maximize the impacts of species promoting the establishment of desirable restoration species (Majer 1989, Archer and Pyke 1991, Longland et al. 2001). It is the hope that the products of this research, as they continue to develop, will help contribute toward our understanding of the roles granivorous animals can have in Great Basin desert restoration.

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Chapter 12 – Economic and social impacts: Costs and acceptability

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INTRODUCTION

This part of the study focuses on the invasion by cheatgrass on the arid rangelands of the Great Basin region. As an aggressive invader, cheatgrass is capable of quickly establishing in areas already subject to disturbance (*e.g.*, fire and overgrazing) (Mack 1985). Numerous ecological studies have analyzed the causes, mechanisms, and effects of invasions by exotic annuals on the arid rangelands of the western U.S. (Hull 1949, Mack and Pyke 1984, West and Young 1988, Melgoza and Novak 1991, Pellant 1990, Emmerich et al. 1993, D'Antonio and Vitousek 1992, and Brooks and Pyke 2001). Specifically analyzing the Great Basin region, Young et al. (1972) identified the factors of loss of perennial grasses and the competitive characteristics of aliens that influenced a change from pristine landscapes comprised of big sagebrush communities and natural wildfire cycles to modern landscapes of exotic annual grasses and woody species.

Mack (1981) provided a detailed account of the successful entry of cheatgrass and other exotic alien annuals on the arid rangelands. The unlimited access to public land and introduction of exotic species resulting in the intensive exploitation of the remote land occurred through the period of 1850 to the 1920's due to homesteading and gold mine discoveries. In addition, the intentional introduction of exotic species from various parts of the world, without complementary inclusion of other native species from their environment to help maintain the ecological balance, contributed to the explosive growth of cheatgrass in a foreign environment. The exploitation of the open range and habitat modification, including homesteading, travels for trade, and open range grazing resulted in disturbed soils and altered fire regimes that allowed for easy seed entry and dispersal of cheatgrass that also provided ideal conditions for growth of cheatgrass and similar species.

All of the above have identified the inherent complexity in biological invasions on arid rangelands. There is a damaging chain of sequential effects on the entire ecosystem that eventually has economic and social consequences. These studies also inferred a common conclusion: adopting a restoration strategy is critical (and often necessary) for effective control of an established invasive species that has crossed an ecological threshold and displaced the native species to attain a newer stable state.

The aim of this study is to assess the economic and social impact of restoration based on an ecological framework developed by the consortium of universities and federal agencies in and around the Great Basin region. The framework is provided by the ecological research described in earlier chapters explores the use of varied restoration strategies to interrupt the cheatgrass induced fire cycle and selects the restoration technique(s) that would control primary weeds like cheatgrass and secondary weeds.

Over the past five decades, there has been a surge in ecological research focusing on the growing threat of biological invasions from cheatgrass. However, little to no research has been conducted on the social and economic impacts of cheatgrass invasion and restoration efforts on ranching and communities supported by ranching. This study assumes significance in the light of a research problem involving a public good and a unique invasive species. Everyone in the U.S. has an equal right to access the public lands (non-exclusionary property), but these users also want conflicting uses resulting in a society possessing mixed views with regard to the use and/or management of the public lands. The goal of this study is to address the economic costs of undertaking restoration and social attitudes of various stakeholders (users) who could possibly have an affect on the support for and/or conduct of restoration activities.

METHODS

The economic and social aspects of this study were completed separately. The economic aspects were analyzed using a multi-period linear programming model of typical ranches within each state. Ecological response data used in the models were estimated using a simulation model based on expected relationships derived from initial studies. The social information was collected using purposive sampling of ranchers, environmentalists, public land managers, and the general public. Each method will be more fully described below.

Economic Modeling Methods

Linear programming was selected to evaluate the cost-effectiveness of the chosen restoration strategies. The least cost based economic assessment approach is used to determine which strategy is the most cost effective. Since all of the benefits of restoration are not easily quantifiable, this study evaluates only the cost-effectiveness of each treatment and identifies the optimum states of restoration given a range of costs. Representative ranches are constructed for each of the four states: Oregon, Idaho, Nevada, and Utah. The linear programming based profit maximization approach accounts for ecological data and stochastic cattle prices.

The research questions we sought to answer using these ranch models were (1) what are the minimum economic costs of controlling cheatgrass infested rangelands and (2) is the adoption of an optimum mix of restoration strategies economically more cost efficient than not adopting any restoration strategy at all. The economic problem characterized by this study is a firm-level constrained cost (revenue) minimization (maximization) type. The study evaluated the economic costs of adopting or not adopting restoration strategies by representative ranches in the Great Basin region. A cost-effectiveness approach is used that assumes the decision to implement a practice has been made and the search is to find the least cost way of achieving the restoration goal.

Four restoration strategies that were used in the economic analysis – spraying a herbicide, grazing, burning, and a combination of all 3 practices. Since the strategies are at various stages across the Great Basin sites, dose-response data are preliminary and limited. The lack of dose-response data was compensated for by developing a simulation model. We are using the simulation software STELLA (Ford 1999 and Deaton and Winebrake 2000) that allows for construction of a simplified competitive ecosystem to simulate the interaction between cheatgrass and the native species.

The STELLA software is used to simulate the interactions between cheatgrass and the native species with the control strategies given a constrained supply of water so as to generate pre-treatment and post-treatment biomass information. Simulated results of pre and post-treatment biomass information from STELLA are used as forage availability constraints in the economic optimization model.

Representative ranches were considered to be profit maximizing firms that have a certain amount of cropland and rangeland available for raising crops and grazing cattle, respectively. Representative ranch models were developed for Idaho, Nevada, Oregon, and Utah. It was assumed that these firms (ranches) operate with a goal to ensure year round forage availability for their cattle that translates into an economic goal of maximizing NPV of the firm's gross margin subject to its resource constraints. Representative ranches were modeled in a multi-period framework so that long run implications for resource availability and transfers due to the adoption of any management decisions during a year are measurable. It was also assumed that ranchers used their BLM grazing permits to graze their cattle on public rangelands and meet their forage needs in summer. The ranch models were constructed using the GAMS software (Brooke et al. 1998).

A baseline optimization model was initially solved for each ranch model across the four study sites. The baseline model included the economic costs of operating the ranch without adoption of any cheatgrass treatments. STELLA generated pre-treatment and post-treatment biomass data were incorporated into the GAMS model. A growth curve was used to select amount of forage available in a given season. The result was that forage utilization may be lower than total annual production. Restoration strategies were then imposed in the STELLA simulation model and post-treatment biomass data of native species and cheatgrass and treatment costs were incorporated into the treatment ranch models. Changes in the forage availability due to the restoration practices caused the model to find a new economic optimum solution.

Social Analysis Methods

It was a proposition of this study that public rangelands are an example where human–environment interactions are based on value systems (either explicit or implicit) and these values are influenced by factors such as situational or geographical context. Furthermore, actions stemming from these contexts may often seem irrational to an economic profit maximizing individual. Adopting rangeland restoration strategies was one such case where changes in the landscape (floral and faunal composition) often influences (and is influenced by) stakeholders who possess varying perceptions. Such differences in perceptions, even if not ultimately translated into actual behavior, can significantly influence their willingness to support and/or assist in the restoration of rangelands. Additionally, the type and degree of feasible restoration techniques are often site and species specific, which calls for a cautious selection of a restoration strategy that fulfills ecologic, economic, and social concerns of acceptability.

This part of the study was exploratory in nature and used a case study approach to elicit attitudes and perceptions of diverse stakeholders who were directly or indirectly affiliated with restoration on public rangelands. The research questions addressed in this study were (1) does restoration have different meanings to different stakeholders across the Great Basin region and (2) what are the key drivers that would enable current restoration strategies to be socially acceptable.

The context here represented unique ecological and socio-economic conditions. The phenomenon of interest in this study was the willingness to support or undertake restoration that can have multiple meanings to varied audiences. This study was a multiple case study design within a single context. Multiple cases existed in this study due to the need to assess attitudes of stakeholders in four different geographic locations. Thus, the unit of analysis (case) also was the meaning of restoration across different geographic locations (southeastern Oregon, southwestern Idaho, northwestern Utah, and northern Nevada). The case study analysis allowed for better understanding of the stakeholders' perceptions given the context (setting) that influenced not only their day-to-day decisions but also their relationship with the natural resources (land, flora, and fauna) and acceptability to change (restoration in this case). Information obtained from this study would complement the economic cost information on impacts of restoration by offering an insight into not only "what it costs to restore" but also "what their attitudes are" with regard to cheatgrass dominated rangelands.

The selection of relevant stakeholders for this study was largely motivated by their expected roles and professions that involve the management and use of public rangelands, on anecdotal evidence, and personal communications. The stakeholders identified for this study were ranchers, informed citizens, interest groups, and agency personnel.

One respondent from each stakeholder group was interviewed in each of the four Great Basin states. Key themes that were expected to emerge from these interviews were the degree of social acceptability to invasive species and cheatgrass control; the assessment of ongoing restoration, including usefulness and methods; and drivers and factors that could improve/affect restoration initiatives. A semi-structured questionnaire was used to allow for the respondent to share his or her views freely and for newer questions to evolve that were not preplanned. Demographic information (age, gender, income, education level, and political orientations) of the participants is collected in an effort to conduct a richer analysis of the data. Moreover, the demographic data in conjunction with attitudinal data allowed for looking at the influence of demographic factors on the perceptions and social acceptability of the participants towards restoration. Yin (2002) warned of limitations to using such a technique, including response bias, inaccuracies in recalling, and reflexivity – interviewee response is what interviewer seeks to hear. For a targeted audience, as in this study, with the possible different meanings of restoration and its overall acceptability embedded in the participant's insights, such a technique was found most appropriate to use.

Phone interviews are conducted in accordance with Oregon State University's (OSU) Institutional

Review Board (IRB) procedures of informed consent and confidentiality of contact information. Data collection through interviews is primarily a three step process. In the first step, informed contacts are used to acquire a list of key informants since the issue is not only very specific in its scope but also limited to the geographical context of Great Basin rangelands of Oregon, Idaho, Nevada, and Utah. In the second step, the key informants are contacted and read the IRB protocol that explains the reason for the interviewer's request to receive names of potential interviewees for each of the four Great Basin states. Snowball sampling is thereafter used to gather names of other potential interviewees for the other states if information from key informants is lacking. The initial sampling pool across all categories for each state will average two names per group although only one person per category will be called for a phone interview. The third and final step involves contacting the interviewees and reading the IRB protocol to them and asking them of their willingness to participate. Those who choose to participate will be either interviewed right then or at another convenient time.

RESULTS AND DISCUSSION

Each representative ranch has a different combination of resources, production rates, management practices, and costs. **Table 12.1** summarizes the initial characteristics of representative Great Basin ranches.

Table 12.1. Initial productivity characteristics of representative ranches.

Characteristics		Units	Oregon	Idaho	Nevada	Utah
Land resources	BLM - natives	AUMs	481	231	550	301
	BLM – treatable	AcresAU	1,031	1,958	3,000	2,055
	Private lease	Ms	200	200	200	200
	Deeded rangeland	AUMs	1,650	1,650	1650	1650
	Raised meadow	Acres	70	70	70	70
	Grazed meadow	Acres	350	350	350	350
Initial animal resources	AUY	AUY	410	513	555	538
	Brood cows	Head	300	330	340	384
	Cull cows	Head	52	57	73	51
	Bulls	Head	20	24	24	18
	Repl. heifers	Head	52	52	65	11
	Horses	Head	10	10	10	10
Required animal raising and transfer conditions	Calf-crop	%	0.84	0.88	0.85	0.80
	Cow replacement	%	0.15	0.15	0.18	0.13
	Bull replacement	%	0.25	0.25	0.20	0.25
	Heifers for sale	%	0.10	0.12	0.11	0.25
	Heifer calves kept	%	0.80	0.80	0.80	0.10
	Cow-bull ratio		20.00	18.00	20.00	24.00
Off ranch income		$	10,000	10,000	10,000	10,000
Family allowance		$	24,000	24,000	24,000	24,000
Fixed ranch expenses		$	17,446	24,430	33,361	23,920
Interest return on savings		%	3	3	3	3
Short term borrowing rate		%	10	10	10	10

Oregon Results

The ecological impact to the Oregon representative ranch under alternative restoration scenarios is shown in **Fig. 12.1**. The different growth functions for cheatgrass and native species (*i.e.*, seasonality) resulted in less forage used than total forage available. Total forage production from BLM "treatable" land was the highest at 1,471 AUMs and consumption was 837 AUMs. Selecting herbicide application resulted in treatable BLM forage availability declining to 821 AUMs and usage to 556 AUMs. Grazing and fire reduced forage availability to 708 AUMs each. A decision to adopt the integrated strategy impacted forage availability and utilization significantly. The integrated scenario resulted in production of 707 AUMs but only 491 AUMs were utilized or a 41% decline for the Oregon ranch model.

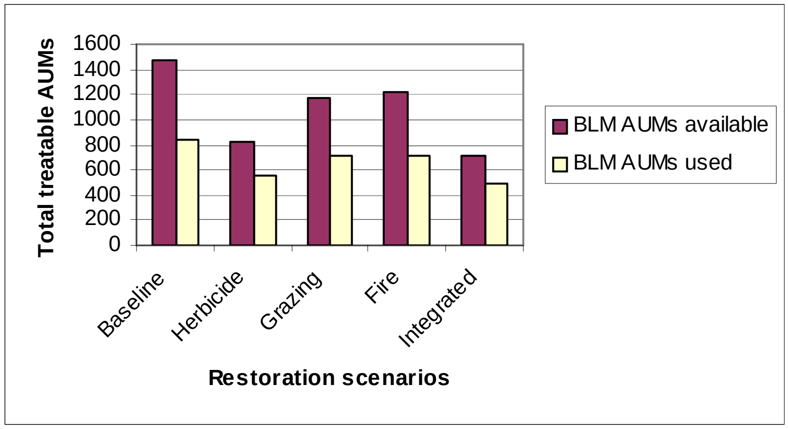

Fig. 12.1. BLM forage availability and use for the Oregon model.

The economic impacts of restoration adoption are summarized below using **Table 12.2**.

Table 12.2. Economic impacts of restoration for the Oregon model.

Characterisitcs	Baseline	Herbicide	Grazing	Fire	Integrated
Animal units yearlong (t = 5 to 36)	462	428	447	449	420
Number of brood cows (t=5 to 36)	300	276	289	290	271
Annual net return (t=5 to 36)	$ 61,827	$ 57,123	$ 60,007	$ 59,767	$ 54,365
Total restoration costs	$ 0	$ 82,815	$ 41,575	$ 57,040	$ 134,365
Restoration costs per hectare	$ 0	$ 197.60	$ 98.80	$135.85	$ 321.10

The economic analysis indicated that adoption of any restoration strategy impacted the ranch financially over not adopting any restoration strategies at all. Net annual returns for the Oregon ranch were highest under the baseline condition alone. Net annual returns were the lowest under the integrated and herbicide restoration scenario with average returns of $54,365 and $ 57,123, respectively. Use of grazing resulted in average net returns of $60,007 and $59,767 with fire. To conclude, grazing and fire proved to be the most cost-effective restoration strategies for the Oregon ranch.

Idaho Results

The representative Idaho ranch is similar to the Oregon ranch in its general working and production practices. The ranch is a full time operation with over 1,958 acres in a BLM allotment available for treatment during the summer grazing months. The ecological impacts to the Idaho representative ranch due to adoption of restoration strategies are shown in **Fig. 12.2**. Under the baseline condition, the Idaho ranch maximized its use of available treatable forage, resulting in cattle grazing 1,450 AUMs of the total available 3,018 AUMs. Dissimilar seasonal growth rates resulted in forage availability never equaling forage production. A management decision to apply herbicide resulted in a reduction in available forage to 1,713 AUMs and final utilization of 1,186 AUMs of treatable BLM land. Adopting grazing as a restoration strategy reduced available forage to 2,536 AUMs and forage grazed to 1,394 AUMs. Prescribed fire use reduced forage availability to 2,526 AUMs and only 1,349 AUMs of those available were finally utilized. The integrated strategy as modeled in STELLA impacted forage availability significantly, resulting in only 1,027 AUMs being grazed (29% decline).

The economic impact of restoration strategies to the Idaho ranch are summarized in **Table 12.3**. Following the summary of individual economic impacts of each restoration strategy, a general discussion reviews the net annual return of the ranch under various restoration scenarios.

Review of the Idaho ranch model indicates that adoption of restoration strategies had similar economic implications as the Oregon ranch model. The baseline condition of no restoration resulted in the highest net return followed by grazing and then fire as cost-effective restoration strategies. Adoption of the integrated restoration strategy impacts the ranch severely in the initial years due to insufficient forage availability. This results in the ranch incurring negative returns until year 3 and then becoming profitable again with increased availability of forage.

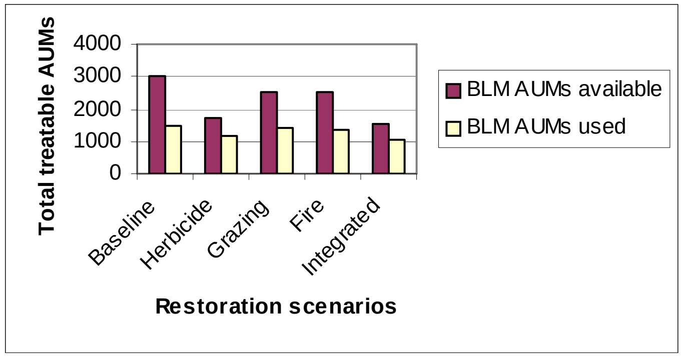

Fig. 12.2. BLM forage availability and use for the Idaho model.

Nevada Results

The ecological impact of restoration to the Nevada ranch is shown in **Fig. 12.3** that compares available versus used BLM treatable forage. Under the baseline conditions, the Nevada ranch model had 3,225 AUMS of which 1,561 AUMs of BLM treatable forage were consumed. Herbicide use reduced cheatgrass growth significantly causing a decline in forage availability to 1,999 AUMs and net use to 1,165 AUMs. Adopting grazing and fire as restoration strategies resulted in the availability of BLM treatable forage to decline to 1,129 AUMs and 1,125 AUMs respectively. The integrated restoration strategy reduced forage availability to 1,682 AUMs and net usage declined to 1,087 AUMs.

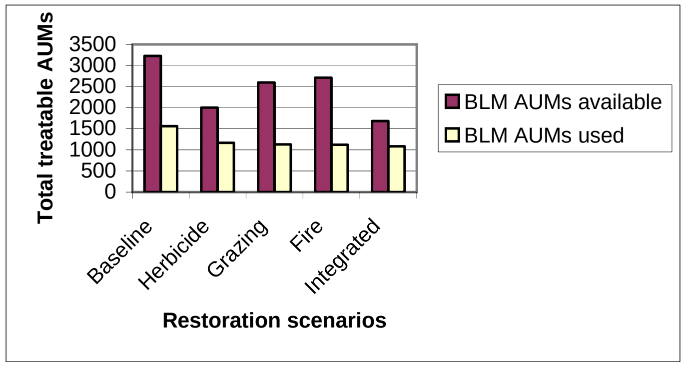

Fig. 12.3. BLM forage availability and use for the Nevada model.

Table 12.4 summarizes the economic impact of cheatgrass control strategies. Similar to the Oregon and Idaho representative ranch, the Nevada ranch was economically impacted by adoption of all four restoration strategies. Although the Nevada representative ranch had a greater BLM allotment area than other representative ranches (1,214 hectare of treatable land), lower precipitation, and a lack of forage availability due to restoration impacted herd size of the ranch significantly. The Nevada ranch maintained an economically viable operation under the baseline and grazing scenarios, but faced the possibility of bankruptcy due to a negative annual net return under the herbicide, fire, and integrated scenarios.

Table 12.3. Economic impacts of restoration for the Idaho model

Characteristics	Baseline	Herbicide	Grazing	Fire	Integrated
Animal units yearlong (t = 5 to 36)	513	483	513	508	460
Number of brood cows (t=5 to 36)	330	308	329	325	294
Annual net return (t=5 to 36)	71,571	67,326	70,701	70,210	62,305
Total restoration costs	0	$182,797	$104,477	$133,847	$280,697
Restoration costs per hectare	0	$229.71	$130.91	$167.96	$353.21

Table 12.4. Economic impacts of restoration for the Nevada model.

Characteristics	Baseline	Herbicide	Grazing	Fire	Integrated
Animal units yearlong (t = 5 to 36)	555	502	490	485	500
Number of brood cows (t=5 to 36)	340	312	300	299	307
Annual net return (t=5 to 36) ($)	65,319	-121,762	51,748	17,274	-92,756
Total treatment costs	0	$ 214,639	$ 94,639	$ 139,639	$ 364,639
Treatment costs per hectare	0	$ 175.37	$ 76.57	$ 113.62	$ 298.87

Utah Results

The ecological impact of cheatgrass control is provided below using **Fig. 12.4**. The representative Utah ranch displayed similar forage availability and use responses to cheatgrass control strategies as did the other Great Basin representative ranches. Under the baseline condition with the higher precipitation range, the ranch's treatable BLM land produced 3,575 AUMs and 1,780 AUMs of those were used. Adoption of an herbicide strategy reduced forage availability to 2,261 AUMs and eventual consumption was 1,190 AUMs. Using grazing as a management strategy resulted in 2,902 AUMs being available and 1,485 AUMs were grazed. Adoption of prescribed fire resulted in the availability of 3,034 AUMs of which 2,023 AUMs were used and an integrated restoration strategy resulted in the ranch utilizing only 1,149 AUMs of the total available 1,897 AUMs.

Table 12.5 summarizes the economic impacts to the Utah ranch choosing to adopt various restoration strategies. The Utah ranch model displays similar economic impacts as the other states. Grazing continued to remain the most cost-effective restoration strategy after the baseline condition. Adoption of herbicide and the integrated restoration strategies proved economically damaging as the ranch runs the risk of going bankrupt.

Table 12.5. Economic impacts of restoration for the Utah model.

Characteristics	Baseline	Herbicide	Grazing	Fire	Integrated
Animal units yearlong (t = 5 to 36)	538	463	524	481	461
Number of brood cows (t=5 to 36)	384	330	374	343	329
Annual net return (t=5 to 36) ($)	51,502	-9,188	49,109	21,227	-30,910
Total treatment costs	0	$173,813	$91,613	$122,438	$276,563
Treatment costs per hectare	0	$207.48	$108.68	$145.73	$330.98

Social Impact Assessment

Stakeholder responses to each question below were analyzed for emerging themes and possible explanations for the respondents' views are discussed.

Question: What does restoration on public rangelands mean to you as BLM Personnel, Rancher, Representative of Environmental Group, or Interested Public?

The key themes that emerged from coding all the responses included: perceptions of restoration, differences in meaning of restoration versus rehabilitation, and barriers to restoration (ecological, economic, and / or social). In general, the findings matched expected results with regard to the organizational responses on the meaning of restoration. All respondents across all groups for each state offered some perception of restoration and contextual factors (ecology and level of awareness and degree of professional involvement with other stakeholders).

Question: What do you think about the ongoing restoration project to control cheatgrass growth and establish native plants instead? Are there alternative approaches that you could suggest?

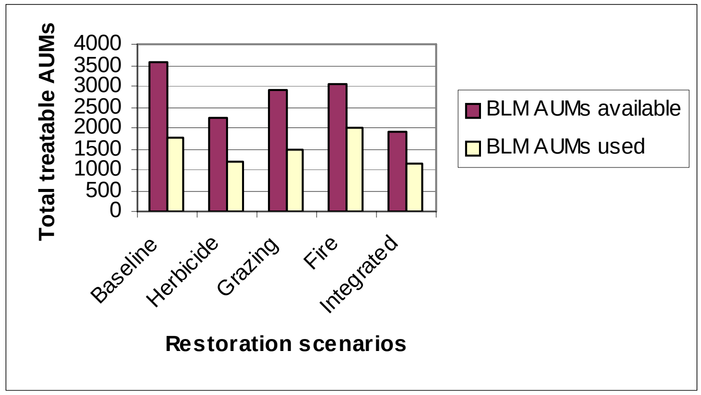

Fig. 12.4. BLM forage availability and use for the Utah model.

The primary themes that emerged from responses to this question were Social acceptability of restoration and Barriers to restoration. In general, BLM respondents across each of the four Great Basin states expressed a high degree of acceptability towards each of the restoration strategies. As inferred in the discussion of the first question, higher levels of precipitation appeared to influence the ranchers' overall social acceptability of adopting restoration strategies. Those ranchers in states with low precipitation were more likely than ranchers in high precipitation states to find restoration a barrier. The informed citizens seemed very well aware of pitfalls associated with cheatgrass invasion and thus the strong need for integrated strategies. All the respondents addressed the economic feasibility of adopting landscape level restoration strategies.

Question: How would you personally support restoration?

The key theme that emerged from reviewing the responses to this question was Ways of supporting restoration: time, money, other ways. Seeking a response from all stakeholders with regard to their notion of costs of restoration resulted in a wide range of estimates. As expected, the BLM and interest group representatives were understandably more aware (due to their occupational specialization) about restoration projects and thus offered itemized breakdowns of costs. In contrast, the ranchers and informed citizens did not offer clear estimates of the costs of undertaking typical cheatgrass control treatments. Only the rancher from Utah emphasized that the ecological context (site specific conditions and history of the region) would influence the economic costs of undertaking restoration.

CONCLUSIONS

Economic Impacts of Restoration Strategies

The adoption of restoration strategies by representative Oregon, Idaho, Nevada, and Utah full time ranches had similar economic implications. All of the null hypotheses are rejected. The study finds that there is a tradeoff between ecological and economic benefits from restoration and the costs of adopting restoration strategies are significantly higher compared to the baseline. Moreover, the costs of adopting the integrated strategy across all four representative ranches are higher than any of the stand alone restoration strategies. Specifically, grazing remains the most cost-effective restoration strategy.

Restoration costs for the four ranches were the highest under the integrated scenario and lowest under a baseline condition. Restoration costs were generally higher for representative ranches in those states that had smaller sized BLM allotments and/or received low levels of precipitation (less than 200 mm). This is seen in the case of Oregon and Idaho representative ranches that had treatable BLM acreages that were smaller than those of Utah and Nevada and also experienced lower levels rainfall resulting in reduced forage availability per hectare. In the case of Nevada (with lower levels of average annual precipitation) and Utah (higher levels of precipitation), treatable BLM acreage was substantially larger, resulting in higher treatment costs.

In summary, the results identified three parameters that may strongly influence the economic costs to Great Basin ranchers due to the adoption of restoration strategies.

1. **Level of precipitation** – The amount of precipitation impacts forage availability and success of restoration (if reseeding is used) that in turn influences herd size and net returns of any representative full time ranch operation.
2. **BLM available "treatable" acreage –** The more of the BLM allotment that is treatable (*i.e.*, infested with cheatgrass), the greater the potential for decreased forage being available if restoration should occur. This would likely cause a ranch to manage a smaller herd and have reduced profits.
3. **Order, type, and time period of restoration strategies –** The sequence of restoration strategies, type of native (or introduced) species used for reseeding, and time period allowed for natives to recover may individually and/or collectively influence total restoration costs. While this was not tested in this study, it is likely important.

Social Impacts of Restoration

In general, the findings matched expected results with regard to organizational responses of the meaning of restoration. All respondents across all groups for each state offered some perception of restoration and contextual factors (ecology, level of awareness, and degree of professional involvement with other stakeholders). There was a consistent response from all four BLM personnel across the four Great Basin states with regard to the existence of a scientific difference in the meaning of restoration versus rehabilitation. The ranchers, in contrast to the BLM respondents, did not think there were any major differences in the interpretations of restoration versus rehabilitation. They also felt that cheatgrass was not necessarily a "problem." The views of the ranchers indicated that their willingness to support restoration was strongly influenced by geographic (levels of precipitation) and ecological (level of cheatgrass invasion) contexts. Moreover, the rancher from Utah was more supportive of restoration than ranchers from the other states, strengthening the hypothesis that higher levels of precipitation increases the overall social acceptability for undertaking restoration. Furthermore, there is also the possible existence of an underlying ideology that "nature's resources is meant for humans to use" in support of the rancher's views that restoration need not occur at the expense of reduced forage availability for cattle. Ranchers also listed economic costs of seeding native species and reduced land available for grazing as a result of restoration as common barriers.

Interest group respondents in support of restoration had similar views as those of BLM personnel with regard to restoration and felt rehabilitation to be a distinctly unique ecological concept. Informed citizens were most expressive about the possible barriers and issues involving restoration projects and educational background was significant in the nature and quality of their responses.

To conclude, across all groups, site specific ecological and demographic factors such as levels of precipitation and educational qualifications influenced interviewee responses. Surprisingly, variations in income levels did not play a critical role in the responses of the respondents. Lastly, findings from the phone interviews strongly supported the possibility that ecological aspects such as precipitation and type of species used in reseeding influenced the degree of social acceptability towards restoration of Great Basin rangelands.

Recommendations for Land Managers

Economic impact assessment of representative Great Basin representative ranches indicates that ranchers alone may not prefer to bear the total costs of restoration on public rangelands. Ecologically, there exists a lack of sufficient information on the accurate responses of cheatgrass to control strategies and the risks associated with seeding native species in low precipitation zones. Development of restoration plans for ranchers should take into account the lack of such dose-response data. The existence of ecological complexities like variation in climatic factors, risks of failure associated with restoration strategies, and spatial growth of invasive species may pose significant economic risks to ranchers. Assessing such risks as part of restoration efforts is appropriate.

Since public rangelands are a public good, it may not be economically efficient for ranchers to support federal and state agencies in undertaking restoration. In general, while there are some private benefits from restoration, it is likely that most of the benefits accrue to society. It may be appropriate to explore the use of (or develop) cost-share mechanisms or innovative policy tools to ensure that cheatgrass control efforts are not only ecologically feasible and socially acceptable but also economically equitable.

Avenues for Future Research

The economic assessment of controlling cheatgrass indicates that cost-effective restoration strategies will lead to reduced profits compared to the baseline scenario of doing nothing. This study, however, was undertaken under the assumption of homogeneity of cheatgrass growth under normal climatic conditions with no other invasive species interacting with cheatgrass when restoration strategies were adopted. Increasing anecdotal evidence of spatial and climatic changes in the Great Basin region calls for future research to explore the economic implications of controlling multiple arid land invasive species in the presence of stochastic events (*e.g.*, rainfall variability and economic market distortions).

Social attitudinal analysis confirmed the existence of variations in perceptions and ideologies held towards restoration and nature of its conduct. Future research directed towards a larger scale survey based analysis of public land users would allow for a better understanding of stakeholders' opinions of invasive species, its management, and overall impression of whether cheatgrass is a "problem" or not. As part of a larger, comprehensive study, conducting an organizational analysis of various federal and state agencies with regard to management of public rangelands would allow for improved understanding of organizational influence on public land managers. Results from the social acceptability analysis also indicate a possibility of differences in perception with regard to use of public rangelands between urban versus rural residents which deserves future investigation.

A simultaneous review of the economic and social impact assessments infer the possible existence of ecological, economic, and social thresholds that influence not only the rate and degree of invasion but also the economic impacts of managing invasion and societal willingness to accept (or reject) such species and its management. An interdisciplinary effort to identify such thresholds and examine if they influence each other would allow for a holistic understanding of the ecology, economics, and human dimensions of arid land invasions by exotic grasses.

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Chapter 13 – Public awareness: Outreach education

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INTRODUCTION

Native rangelands, particularly sagebrush-grassland communities, are disappearing in the Great Basin. There are a number of causes; however, two factors are universally implicated – the invasion of weeds such as cheatgrass (*Bromus tectorum*) and wildfire. Cheatgrass and fire create a vicious cycle. Fire can open up sagebrush-grassland communities for cheatgrass to invade. Cheatgrass provides continuous fine fuels for subsequent fires, which facilitate the spread of cheatgrass and other weeds. These fires and weeds have dramatic impacts on native plant species, wildlife species and their habitat, livestock forage, recreational values, water and air quality, and soil health. Fires also cost millions of dollars annually to control and rehabilitate.

Public awareness of invasive weeds and their impacts is lacking (Colton and Alpert 1998). In addition, few people know what research is being conducted on invasive weeds, and much less understand why it is being done and what the potential implications may be (Field and Powell 2001). A major challenge for those involved in formal and informal public education is to design and implement effective methods of explaining research and to find channels of communication that are readily accessible to the public. The objective of this subcomponent of the IFAFS project is to use partnerships with educators to increase student and public awareness of invasive species issues and to develop educational tools that convey solutions to invasive species and native plant restoration problems.

APPROACH

Several approaches were used to promote awareness of invasive weed issues in the Great Basin for K-12 students, undergraduate students, and the general public.

K-12 Teacher Workshops

Partnerships were established with several organizations to include a unit on weed ecology, management, and research in existing K-12 teacher workshops in Idaho and Oregon. The unit, at least one day in length, provided teachers with an overview of cheatgrass/secondary weed issues in their area, invasion ecology concepts, weed characteristics and species identification, integrated weed management approaches on public and private lands, federal and state research programs, and public involvement programs. Teachers participated in field tours that featured hands-on activities (plant identification, vegetation monitoring, and release of biocontrol insects) and discussions of weed management and research projects with scientists, land managers, and/or county weed supervisors. Teachers were provided numerous resources, including weed models, weed identification cards and field guides, examples of available curricula emphasizing weeds/invasive species, lists of internet resources and technical publications, and contact information for local, state, and federal agencies involved in weed management. The K-12 teacher workshops, and sponsoring organizations, included:

- Rangeland Ecology Teacher Workshop, July 18-22, 2005, and June, 26-30, 2006, McCall, Idaho; sponsored by the Idaho Rangeland Resource Commission and Rangeland Ecology and Management Department, University of Idaho.
- Wildfire and Weeds Teacher Workshop, July 18-19, 2006, Boise, Idaho; sponsored by Project Learning Tree and the Idaho Rangeland Resource Commission.
- Summer Agricultural Institute Teacher Workshop, July 9-14, 2006, La Grande, Oregon; sponsored by the Oregon Agricultural Education Foundation and Oregon State University.

Undergraduate Case Studies

Together with lectures and labs, case studies assist students in acquiring content knowledge, process skills, and an understanding of the context and application of science to their daily lives (Camill 2006). Cases are typically written as dilemmas that give a history of an individual, institution, or organization faced with a problem that must be solved. The goal of the instructor is to help students work through the facts, analyze the problem, and then consider possible solutions and consequences of the actions they might take (Herreid 1994).

A case study, *Breaking the Cheatgrass-Fire Cycle on Northern Great Basin Rangelands*, was developed for a Wildland Vegetation and Habitat Management course at Utah State University (USU). The case presents an overview of human-mediated disturbances, the introduction of cheatgrass and secondary weeds, the cheatgrass-fire cycle, and the ecological and socioeconomic impacts of weeds and wildfires on rangelands in the northern Great Basin. Background information (plant community descriptions, soils, climate, topography, historical uses, fire history, vegetation treatments) is given for a specific area encompassing private lands (cattle rancher) and public lands (Bureau of Land Management) in northern Nevada. A list of human and equipment resources is also provided. Students develop a vegetation manipulation/restoration plan to achieve a set of objectives: 1) break the cheatgrass-fire cycle in cheatgrass-dominated areas, 2) reduce the fire hazard and improve the diversity of existing crested wheatgrass seedings, and 3) protect remaining native sagebrush-grassland communities from wildfires. The plan must address the key ecological parameters related to the problem and objectives and propose and justify vegetation manipulation/restoration treatments to meet the objectives. Students prepare a plan individually, and then compare and contrast their plans with those of their peers in a directed discussion in class. Modules can be added to the case to make it applicable to other courses, *i.e.* an economic evaluation for a natural economics course, and a characterization of introduced and native restoration species or impacts of vegetation manipulation treatments for an environmental science course. A final version of this case study will be sent to the National Center for Case Study Teaching in Science at the State University of New York, Buffalo, with a request to post it on their case study website.

Undergraduate Research Experience

Undergraduate students at colleges and universities in or adjacent to the Great Basin had the opportunity to participate in research and education experiences associated with the IFAFS project. In 2004, an Undergraduate Research Experience Grant Program was established to solicit grant proposals from interested students (and faculty advisors). Mini-grants ($4,000) were available to support research experiences and a presentation at a state, regional, or national meeting of a professional society. The research proposals received in 2004 were not funded because they were considered tangential to the IFAFS project. The undergraduate research experience was modified to allow IFAFS project scientists at Oregon State University (OSU), Utah State University, and the University of Nevada, Reno (UNR), to select students to be involved in IFAFS research and education projects. Each student would receive $4,000 to cover wages, research expenses, and travel costs. In 2005, one student participated in a research experience at OSU, and one at UNR, and three students (sharing $4,000) participated in an interpretive education experience at USU. In 2006, one student participated in a research experience at UNR, and one at USU, and one student participated in an interpretive education experience at USU.

Research Site Tours

Research findings from the IFAFS project, and general information about the ecology and management of Great Basin rangelands, were presented to different audiences at the project sites in Utah, Nevada, Oregon and Idaho.

In Utah, the Simpson Springs site was included in a June 2005 field tour on weeds, wildfire, and restoration, sponsored by the Utah Section of the Society for Range Management. About 30 scientists, land managers, and university students participated in the tour. In June 2006, a science writer for the Salt Lake Tribune visited the Simpson Springs site. His article, *Invasive Weeds Threaten Native Species,* *Cause Havoc*, appeared in the July 6, 2006 edition of the Salt Lake Tribune. As a result of that article, Utah Public Radio (KUSU) interviewed Chris Call for radio spots (*Research Matters*) about invasive plants and the IFAFS project, which were aired in August and September 2006.

In Nevada, field tours were held during seeding time periods to demonstrate improvements to the Truax drill that the IFAFS group had made and to discuss the experiments in fall 2003 and 2005. In addition, BLM employees from the Winnemucca and Elko field office toured the Eden Valley NV study area and discussed initial results in mid-summer 2005. Finally, the IFAFS studies were discussed during the 2003, 2004, and 2005 Great Basin Ecosystem Management Project Field Tour by the USFS Rocky Mountain Research Station during mid-summer.

In Oregon and Idaho, field tours were held for the Society for Range Management Pacific Northwest Section in summer 2005 and for the USGS National Research Program Leaders in summer 2006.

Traveling Exhibit

Because only a very small percentage of the public's understanding of the world and, in particular, its understanding of environmental conservation and sustainability is gained through formal education (Ballantyne and Packer 2005; Dierking and Falk 2003; Falk 2005), free-choice learning plays an important role in enhancing public understanding of environmental issues. When asked where they acquire most of their science learning, the majority of people claimed to have learned science informally, through free-choice learning opportunities which they themselves sought out: the internet, magazines and books, museums, zoos, aquariums, and participating in special-interest clubs and programs (Dierking and Falk 2003). The field of informal public education can reach the public at all levels so that those who need the information most, *i.e.*, those who make or will make decisions for themselves and their families, have access to accurate, up-to-date, unbiased, and substantive information (Field and Powell 2001).

A traveling exhibit, consisting of 10 panels (each 0.75m X 1.05 m) was designed to promote learning for a widely varied audience in many different settings. It will travel to middle schools as well as libraries, museums, nature centers, town halls, or other places of community gathering. The exhibit incorporates essential components of exhibit design as described by Bitgood (1992). Specifically, his research showed that: (1) small units of information are more likely to be read; (2) high contrast between print and background increases reading; (3) larger point size produces greater visitor attention; and (4) presenting the information in a manner that makes it easy to scan usually results in more effective communication. From literature on visitors and the meaning of structure of text, Bitgood (1992) also found that: (1) visitors learn just as much when key ideas are presented as they do when given traditional paragraphs of text; (2) visitors are more likely to read when questions are used as headers; and (3) subject matter that connects to the visitor in a meaningful way is more likely to be read. The traveling exhibit follows this format by using questions as titles on each of the panels, breaking text into small pieces, using images rather than words wherever possible, using large font sizes and dark text on light backgrounds, and presenting key ideas rather than detailed descriptions of complex concepts.

Panels 1 through 8 are displayed in four, double-sided frames in circular fashion, radiating from a center post. The titles and topics of the panels are: (1) *What's the BIG problem?*, which presents the ecological and socioeconomic impacts of weed invasion in the Great Basin; (2) *What are the weapons of weed invasion?*, which highlights characteristics that allow three prominent weeds to invade plant communities; (3) *How do we put out the welcome mat?*, which describes the role of human-mediated disturbance in facilitating weed invasion; (4) *How healthy is your land?*, which uses a comic strip illustration to depict the cheatgrass-fire cycle and introduce the concept of the state and transition model of plant succession; (5) *What's in the manager's toolbox?*, which describes the components of integrated weed management; (6) *Who's digging for answers?*, which highlights five current research efforts, four of which are from the IFAFS project; (7) *Who's pitching in to pitch out weeds?*, which highlights current citizen efforts to monitor and manage weeds in the Great Basin; (8) *What can YOU do?*, which describes some specific ways in which individuals decrease the spread of weeds as well as help detect and report weed infestations in their area.

Panels 9 and 10 are displayed on a separate double-sided display between two posts. The titles and topics of the panels are: (9) *Do you know your Great Basin natives?*, which has images with identifying characteristics for six important native plants; and (10) *How will you know a weed when you see one?*, which has images and identifying characteristics for six important weeds that have invaded Great Basin rangelands.

Though the exhibit panels provide a tool for free-choice learning for several audiences, there are some drawbacks to focusing solely on free-choice learning opportunities. The lack of an opportunity for both preparatory and follow-up activities is a shortcoming of informal learning settings. It is important to integrate free-choice and formal learning about environmental issues so that learners will adopt sustainable attitudes and behaviors and will then continue to explore and develop their relationship with the environment throughout their lives (Falk 2001; Ballantyne and Packer 2005). Therefore, a teaching activity matrix was developed for middle school teachers. The matrix organizes currently available resources with activities that are well designed and can be very easily adapted to address the specific issues presented on the exhibit panels. The activities listed in the matrix can all be found in well known and widely distributed resources like Project Learning Tree, Project Wild and Project Wet, or in easily accessible resources such as Aliens in Your Neighborhood. These specific and tangible learning activities will help learners to think critically about their choices, and provide them with opportunities to apply the action skills taught through the exhibit.

Formative evaluations were used in the development of the third and final version of the exhibit. All feedback was qualitative, and was gained either through individual written comments or through comments recorded during discussions. Evaluators included: K-12 teachers at the Rangeland Ecology Teachers Workshop in McCall, Idaho, in 2005 and 2006; IFAFS scientists; members of the Utah-Idaho Cooperative Weed Management Area; students and teachers from Mount Logan Middle School in Logan, Utah; the exhibit designer at the Utah Museum of Natural History in Salt Lake City, Utah; an Extension weed specialist at Utah State University; and the director of the Ogden Nature Center, Ogden, Utah. Comments and suggestions focused on reducing wordiness, reducing highly technical language, incorporating more visual material, incorporating a cartoon character, providing a take-home brochure, breaking up text into smaller blocks, using metaphors to explain complex concepts, and creating plant identification panels that would help people recognize important native plants and invasive weeds. All of these comments and suggestions were incorporated into the final version of the exhibit.

The final version of each panel is being printed onto a high-pressure laminate material, which will be displayed on aluminum framing systems. The exhibit will be ready to travel to middle schools, nature centers, libraries, etc., in February 2007.

Web Site

The World Wide Web is an environment that provides the learner freedom and opportunity for informal learning. According to Wang and Bagaka (2003), self-exploration is a key element of web-based learning. This necessitates presenting information in an interesting way to capture the attention of the learner, and educate them quickly before they move on (Wolfe 2001). Since visitors will range from K-16 teachers and students to public and private land managers to the general public, information needs to be concise, interesting, and understandable to a wide range of audiences. The design of the website follows Merrill's (2001) principles of instructional design, *i.e.*, learning is facilitated when: (1) the learner is engaged in solving a real-world problem; (2) new knowledge builds on the learner's existing knowledge; (3) new knowledge is demonstrated to the learner; (4) new knowledge is applied by the learner; and (5) new knowledge is integrated into the learner's world. The design and layout of the website also follows the principles of visual design, including color usage, and the use and arrangement of pictures, graphics, quotes and organizational lines. Some repeating elements such as color, logo, heading patterns, etc., help maintain unity within pages and throughout sections.

Many of the impacts associated with invasive weeds in the Great Basin, particularly the cheatgrass-fire cycle and reductions in familiar wildlife species, can be engaging, real world issues. Website visitors will vary in terms of background knowledge, but most should have some experience with weeds in yards/gardens, and many will understand the danger of fires and how they impact the landscape. The web pages build on these and other familiar aspects of the issue, provide a scientific background for understanding the problem, and show what is being done to solve it through the IFAFS project example. There are principles that learners can apply in their own lives, *i.e.*, through plant identification (particularly invasive species) and good practices of weed-spread prevention. This knowledge must become a part of the learner's world for the educational experience to be effective.

The web pages have been organized in a manner similar to that for the traveling exhibit: (1) an overview of Great Basin ecology, focusing on the ecological and socioeconomic impacts of invasive weeds, particularly cheatgrass; (2) the role of natural and human-mediated disturbances in weed invasion and plant succession; (3) descriptions of important native species, invasive weed species, and introduced restoration species; (4) morphological and physiological traits of invasive weeds; (5) research projects focused on weed ecology and restoration, particularly the IFAFS project; (6) a description of the components of integrated weed management; and (7) examples of community efforts to monitor and manage invasive weeds, and ideas for individual actions.

Other items on the website include a glossary of terms and sidebars featuring IFAFS project personnel. The glossary is a database that is accessed by the visitor upon selecting a hyperlinked word that is unfamiliar to them. A definition will then be displayed. Our intention is to provide definitions for increased understanding while minimizing breaks in the reading process. Project personnel were included in sidebars on selected web pages because featuring scientists provides a personality behind the research, and has been found to be an effective way to communicate science to the public (Mitsuishi et. al. 2001).

The first version of the website will be available for evaluation by IFAFS project scientists, teachers, students, land managers, and the general public in January 2007. Individuals will be asked to view the website and provide feedback. After revision, the website will be posted on the Range Extension server at Utah State University, Logan, Utah.

IFAFS Symposium

A summary of the IFAFS project findings will be presented in a 4-hour symposium at the 60th Annual Meeting of the Society for Range Management in Reno, Nevada, on February 12, 2007.

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PART II – PRODUCTS AND DELIVERABLES

PART II – PRODUCTS AND DELIVERABLES

1. **Publications**
   a. **Submitted manuscripts**

Hempy-Mayer K, Pyke DA (Submitted) Defoliation effects on *Bromus tectorum* seed production: implications for grazing. Rangeland Ecology and Management.

   b. **Published manuscripts**

Allcock K., Nowak R, Blank B, Jones T, Monaco T, Doescher P, Tanaka T, Ogle D, St. John L, Pellant M, Pyke D, Satyal V, Tanaka J, Schupp E, Call C (2006) Integrating weed management and restoration on western rangelands. *Ecological Restoration* 24:199-200.

Busso CA, Mazzola M, Perryman BL (2005) Seed germination and viability of Wyoming sagebrush in northern Nevada. *Interciencia* 30:631-637.

Pyke DA, Knick ST (2005) Plant invaders, global change and landscape restoration. African Journal of Range and Forage Science 22:73-83.

Pyke DA, McArthur TO, Harrison KS, Pellant M (2003) Coordinated intermountain restoration project – fire, decomposition and restoration. Pp 1116-1124 IN: Allsopp N, Palmer AR, Milton SJ, Kirkman KP, Kerley GIH, Hurt CR (eds). Proceedings of the VIIth International Rangelands Congress, 26th July-1st August 2003, Durban, South Africa. Document Transformation Technologies, Irene, South Africa

2. **Presentations**
   a. **Invited presentations & posters**

Nowak RS (2002) Integrating Weed Control and Restoration on Western Rangelands. Invasive Plants and Restoration in the West: A Partnership Workshop, Center for Invasive Plant Management, Montana State University, Salt Lake City UT.

Pyke DA (2004) Restoration and rehabilitation – Bridges to build, impediments to success. Special Symposium: Fighting the odds: the challenge to save the sagebrush biome. Ecological Society of America, Portland OR

Pyke DA (2006) Can we reverse the annualization of the Great Basin? Invited Seminar, Department of Ecology and Evolution, University of Oregon, Eugene,OR

Pyke DA, Knick S (2005) Pulling back from the edge: Sage grouse, invasive grasses and restoration. Managing Invasive Species while Protecting Endangered Species: A Symposium. Eastern Weed Science Society of America, Washington DC.

Schupp EW, Chambers JC, Pyke D (2003) Competition and the restoration of cheatgrass-infested rangelands. Coordinated Intermountain Restoration Project Meeting on Great Basin Restoration, Boise ID.

Schupp EW, Chambers JC, Pyke D, Nowak R (2003) Competition and the restoration of cheatgrass-infested rangelands. 7th Biennial Conference Integrating Science and Management on the Colorado Plateau, Symposium on "Evolution and Management of Invasive Weeds", Flagstaff AZ.

NOTE: The following symposium and presentations are scheduled for the Society of Range Management 2007 Annual Meeting

Call CA, moderator (2007) Symposium: Integrating Weed Control and Restoration on Great Basin Rangelands. Society for Range Management Annual Meeting, Reno NV – February 12, 2007

- *Cheatgrass, secondary weeds, and restoration issues in the Great Basin* – Bob Nowak and Mike Pellant
- *Site preparation, seeding equipment, and plant materials selection* – Dan Ogle, Tom Jones, and Loren St. John

Screening native cultivars as a transition community – Tom Monaco, Tom Jones, Jacob Landmesser, and Bob Nowak

Integrating soil communities of sagebrush steppe and Bromus tectorum-invaded ecosystems with restoration efforts across the Great Basin – Nicole M. DeCrappeo and David A. Pyke

The Effect of sucrose application on soil nutrient availability – Robert Blank, Jeff Burnham, Jeanne Chambers, Andrew Lindgren, Monica Mazzola, Christo Morris, and Robert Nowak

Plant functional groups and soil N: cheatgrass and native plant responses – Monica Mazzola, Kim Alcock, Jeanne Chambers, Dave Pyke, and Gene Schupp

Plant functional groups and soil N: secondary weed responses – Paul S. Doescher, David A. Pyke, and Eugene W. Schupp

Integrated statistical strategies, or making sense of site differences – Kimberly Allcock and Nicole DeCrappeo

Rodent granivory and ecological restoration – Steve Ostoja and Eugene Schupp

Integrating weed management and restoration on Great Basin rangelands: management options and applications to larger scale – Lisa Ellsworth, Jacob Landmesser, Kimberly Allcock, and Bob Nowak

Economic and social impacts: costs and acceptability – Vijay Satyal, John Tanaka, Denise Lach, David Pyke, and Paul Doescher

Public awareness: outreach education – Chris Call, April Phillips, and Bracken Henderson

b. Contributed presentations and posters at local/regional/national meetings

Allcock K, Blank R, Chambers J, Doescher P, Mazzola M, Nowak R, Pyke D, and Schupp E (2005) Integrating Weed Control and Restoration on Western rangelands. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

Allcock K, Lortie C, Nowak R (2004) Can resource pulsing determine community invasibility? Water and cheatgrass in Great Basin sagebrush steppe. Ecological Society of America Annual Meeting, Portland OR.

Allcock, KA, Mazzola M, Nowak R, Chambers C, Blank, R, Doescher P, Pyke D, Schupp E (2006) Integrating weed control and restoration on western rangelands: A functional group approach. Nevada Wildland Fire and Outreach Conference, Reno NV.

Allcock K, Nowak R, Wilson C (2003) Integrating weed control and restoration on Western Rangelands. CAL-IPC Annual Meeting, King's Beach CA.

Brunson J, Pyke DA (2006) Yield responses of invasive grasses to doses of sucrose. Ecological Society of America Annual Meeting, Memphis TN.

Burnham JS, Schupp EW, Monaco TA (2005) Competition between bluebunch wheatgrass, cheatgrass, and squarrose knapweed under different nutrient regimes. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

Burnham JS, Schupp EW, Monaco TA (2006) Competition between bluebunch wheatgrass, cheatgrass and squarrose knapweed under factorial nitrogen-phosphorous regimes. Fourteenth Wildland Shrub Symposium, Cedar City UT.

Busso CA, Mazzola M, Perryman BL, Glimp HA (2004) Seed weight and its relationship to environmental variables and germination in *Artemisia tridentata* ssp. *wyomingensis*. International Conference of the Society for Ecological Restoration, Victoria BC, Canada.

DeCrappeo NM, PykeDA (2003) Soil biotic community dynamics in native and cheatgrass-dominated sagebrush steppe ecosystems. Coordinated Intermountain Restoration Project Annual Meeting, Boise ID.

DeCrappeo NM, PykeDA (2004) Soil crusts and critters in cheatgrass-dominated sagebrush steppe ecosystems. Coordinated Intermountain Restoration Project Annual Meeting, Reno NV.

DeCrappeo NM, PykeDA (2005) Belowground communities respond to restoration strategies in *Bromus tectorum*-invaded ecosystems in the northern Great Basin. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

DeCrappeo NM, PykeDA (2006) Soil microbial and nematode community dynamics under elevated and depleted nitrogen conditions in paired sagebrush steppe and *Bromus tectorum*-invaded ecosystems. Ecological Society of America Annual Meeting, Memphis TN.

Landmesser J, Allcock K, Nowak R (2005) Integrating Weed Control and Restoration on Western Rangelands. 8th Biennial Conference of Research on the Colorado Plateau, Flagstaff AZ.

Landmesser J, Jones T, Monaco T, Nowak R, Pyke D, Schupp E (2005) Success of cheatgrass (*Bromus tectorum*) control and native plant restoration techniques on western rangelands. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

Louhaichi M, Pyke DA, Shaff S, Johnson DE (2006) Development of technologies to map slick spot soils on the Snake River Plain. Society for Range Management Annual Meeting, Vancouver BC, Canada.

Mazzola MB, Chambers JC (2006) Effects of sucrose addition and seeding density on native species and cheatgrass establishment in sagebrush ecosystems. Ecological Society of America Annual Meeting, Memphis TN.

Mazzola MB, Chambers JC (2006) Restoration of cheatgrass dominated ecosystems: effects of sucrose addition and seeding density on seedling establishment. First Annual Nevada Wildland Fire Research and Outreach Conference, Reno NV.

Nowak RS (2005) Integrating weed control and rangeland remonstration in Nevada. Eastern Nevada Range Research Field Day, Ely NV.

Nowak R, Allcock K, Ellsworth L, Landmesser J (2006) Integrating weed management and restoration on Great Basin rangelands. University of Nevada, Reno CABNR Open House. July 2006, Reno NV.

Nowak RS, Chambers JC, Doescher PS, Pyke DA, Schupp EW (2003) Integrating weed control and restoration on Great Basin rangelands. Invasive Plants in Natural and Managed Systems-Ecology and Management of Alien Plant Invasions Workshop, Ft. Lauderdale FL.

Ostoja SM, Schupp EW (2005) Evidence for indirect effects in seed removal by granivorous rodents in the Great Basin of Utah. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

Ostoja SM, Schupp EW (2005) Evidence for indirect effects in seed removal rates mediated by seed harvesting rodents and ants in two vegetation types in the Great Basin of Utah. Society for Range Management Annual Meeting, Fort Worth TX.

Ostoja SM, Schupp EW (2006) Total seed densities and relative proportions affect seed preferences by granivorous rodents. Ecological Society of America Annual Meeting, Memphis TN.

Pellant M, Pyke D, Shaw N, Nowak B, McIver J (2004) Linking science and management to accomplish restoration in the Great Basin Desert. Ecological Society of America Annual Meeting, Portland OR.

Rieder JP, Ostoja SM, Newbold TAS (2006) Effect of cheatgrass on locomotor ability of rodents and lizards: That stuff is dense! Ecological Society of America Annual Meeting, Memphis TN.

Satyal V, Tanaka JA, Lach D, Pyke DA, Doescher P (2006) Economic and Non-Economic Impacts of Restoration: A Case Study Analysis of The Great Basin Region. Western Agricultural Economics Association Annual Meeting, Anchorage AK.

Witwicki D, Doescher P, Pyke D, Perakis S (2005) Sugar application and nitrogen pools in Wyoming big sagebrush communities and exotic annual grasslands. Ecological Society of America Annual Meeting, Montreal Quebec, Canada.

c. Seminars and other presentations

Allcock K (2004) Integrating weed control and restoration on western rangelands. BLM Science Committee, Reno NV.

Mazzola MB (2006) Restoration of sagebrush ecosystems. Ecolunch Seminar, University of Nevada Reno, Reno NV.

Nowak RS (2002) Integrating weed control and restoration for Great Basin Rangelands. Presented to State BLM Offices for Idaho (June 19), Nevada (June 17), Oregon (April 16), and Utah (July 5); to Elko Field Office (July 24).

Nowak RS (2004) Integrating weed control and restoration for Great Basin Rangelands. Presented to BLM Carson Field Office.

3. Theses and dissertations

Bekedam S (2004) Establishment tolerance of six native sagebrush steppe species to Imazapic (PLATEAU) herbicide: implications for restoration and recovery. M.S., Botany & Plant Pathology, Oregon State University, Corvallis OR.

Burnham JS (*In progress*) Relationship of selected soil nutrient levels to competition between a native perennial grass, an exotic annual grass, and an exotic perennial forb. M.S., Ecology, Utah State University, Logan UT.

DeCrappeo NM (*In progress*) Integrating soil communities of sagebrush steppe and Bromus-tectorum invaded ecosystems with restoration efforts across the Great Basin. Ph.D., Crop and Soil Science, Oregon State University, Corvallis OR.

Hempy K (2004) Effects of defoliation on *Bromus tectorum* seed production and growth. M.S., Botany & Plant Pathology, Oregon State University, Corvallis OR.

Henderson B (*In progress*) Invasive Weed Management in the Great Basin: Informal Web-based Education M.S. in Range Science, Department of Wildland Resources, Utah State University, Logan UT.

Mazzola MB (*In progress*) Spatial heterogeneity and habitat invasibility in sagebrush ecosystems. Ph.D., Ecology Evolution and Conservation Biology Program, University of Nevada Reno, Reno NV.

Ostoja SM (*In progress*) Granivory in the context of Great Basin desert restoration: implications of seed predation and seed dispersal by small mammals and harvester ants. Ph.D., Ecology. Utah State University, Logan UT.

Phillips A (*In progress*) Alien Invaders: Weeds in the Great Basin, An Educational Traveling Exhibit M.S. in Human Dimensions of Ecosystem Science and Management, Department of Environment and Society, Utah State University, Logan UT.

Satyal VH (2006) Economic and social impacts of restoration: A case study of the Great Basin region. Ph.D., Environmental Science, Oregon State University, Corvallis OR.

Witwicki D (2005) Sugar applications and nitrogen pools in Wyoming big sagebrush communities and exotic annual grasslands. M.S. Environmental Sciences, Oregon State University, Corvallis OR.

4. Field tours – *Citation format:* Tour leader (year) Tour group name. Tour location.

Burnham JS (2005) Brigham Young University Restoration Ecology Class. Vernon Hills UT.

Call CA, Schupp EW, Burnham JS, Ostoja SM, (2005) Summer Tour of the Utah Section of the Society for Range Management. Simpson Springs UT.

Mazzola MB (2003) The Great Basin Ecosystem Management Project Field Tour, USFS Rocky Mountain Research Station. Austin, NV.

Mazzola MB (2004) The Great Basin Ecosystem Management Project Field Tour, USFS Rocky Mountain Research Station. Austin, NV

Mazzola MB (2005) The Great Basin Ecosystem Management Project Field Tour, USFS Rocky Mountain Research Station. Austin, NV.

Nowak R (2006) BLM representatives, Elko Field Office. Izzenhood Ranch NV.

Nowak R, Wilson C (2003) BLM, State, and NGO representatives, Winnemucca and Elko Filed Offices. Eden Valley NV.

Pyke DA (2005) Society for Range Management Pacific Northwest Section. Oregon IFAFS Research Sites.

Pyke DA (2006) USGS National Research Program Leaders. Oregon IFAFS Research Sites.
Schupp EW (2004) Idaho-Nevada-Utah Interagency Plant Materials Committee. Idaho IFAFS sites.

5. Other outreach activity

Press release from University of Nevada Reno: "Researchers mobilize to break the cheatgrass-fire cycle". Newspapers from around the western US printed the release. http://www.ag.unr.edu/cabnr/Newsletter/FullStory.asp?StoryID=19

Development of a traveling exhibit and a website (Bracken Henderson) focusing on weed ecology, management and research, and community action in the Great Basin. The exhibit and website will be completed by November 2006.

"Research Matters" radio spots about invasive plants and the IFAFS project on Utah Public Radio (KUSU) in August and September 2006.

Article on cheatgrass ecology and impacts in the Salt Lake Tribune on July 6, 2006.

Teacher workshops on rangeland ecology and invasive weeds in Idaho in July 2005, and June and July 2006, and in Oregon in July 2006.

PART III – HUMAN RESOURCE DEVELOPMENT

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Abbreviations used in this section include:

- Aberd = NRCS Aberdeen Plant Materials Center
- ARS-L = USDA ARS Research Laboratory, Logan UT
- ARS-R = USDA ARS Research Laboratory, Reno NV
- OSU = Oregon State University
- UNR = University of Nevada, Reno
- USFS = USFS Rocky Mountain Research Laboratory, Reno NV
- USGS = USGS Forest and Rangeland Ecosystem Science Center, Corvallis OR
- USU = Utah State University

1. Postdoctorate Fellows

Allcock, Kim – UNR

2. Technical Support Staff

Allen, Fay – ARS-R
Bair, Charles – Aberd
Blonski, Laura – USU
Burnham, Jeffrey – USU
Cornforth, Brent – Aberd
DeCrappeo, Nicole – USGS
Ellsworth, Lisa – UNR
Hereford, Mark – USFS
Hesse, Cedar – OSU
Lair, Tim – USGS
Landmesser, Jacob – UNR
Lindgren, Andrew – USGS
Montblanc, Genie – UNR
Morgan, Tye – ARS-R
Morris, Christo – USU
Moseley, Kendra – UNR
Salo, Cindy – USGS
Schwartz, Elizabeth – USGS
Shaff, Scott – USGS
Simonson, Boyd – Aberd
Tilley, Derek – Aberd
Wilson, Carlos – UNR

3. Graduate Students

Bekedam, Steven – MS, OSU; 2004
Burnham, Jeffrey – MS, USU; *in progress*
DeCrappeo, Nicole – PhD, OSU; *in progress*
Hempy, Kara – MS, OSU; 2004
Henderson, Bracken – MS, USU; *in progress*
Mazzola, Monica – PhD, UNR; *in progress*
Ostoja, Steven – PhD, USU; *in progress*
Phillips, April – MS, USU; *in progress*
Satyal, Vijayanand H. – PhD, OSU; 2006
Witwicki, Dana – MS, OSU; 2005

4. Research Internship for Undergraduates

Gearhart, Jessica. Vegetation response following release from grazing pressure in a sagebrush (*Artemisia tridentata ssp. wyomingensis*) grassland in northwestern Nevada. Final Report for IFAFS Research Internship, June-August 2006.

Lewis, April. Final Report for IFAFS Research Internship.

Logan, Tyler. Seed preferences of harvester ants for common eastern Great Basin vegetation types. Final Report for IFAFS Research Internship, June-August 2006.

Marshall, Taylor. Phosphorus and Nitrogen Fertility at Bedell Flats. Final Report for IFAFS Research Internship, June-August 2005.

5. Short-term and Summer Assistants

Bailey, Kyle – UNR
Bertelsen, Luke – USFS
Blaisdel, Kai – USGS
Dykstra, Susan – USFS
Kowalchuk, Cindy – USFS
LaMalfa, Melissa – USU
Larimer, Audrey – USGS
Nelson, Kara – USU
Sanders, Erin – USGS
Sheftall, William – USFS
Shuppert, Dave – USGS
Vicenzio, Ken – USFS

Fonnesbeck, Maria – USU
Fontaine, Joe – USGS
Johnson, Danielle – USFS
Knutson, Kevin – USGS
Orling, Emily – USGS
Redd, Richard – USFS
Salmon, Olivia – USU
Samples, Jessica – USGS
Whitacre, Marina – USU
Williams, Justin – USU
Wojtowitz, Todd – USGS
Wyman, Melissa – USFS

6. Undergraduate Students

Atkins, Bridget – USU
Barker, Ryan – USU
Bower, William – USU
Bracken, David – USU
Christensen, Dan – USU
Curl, John – USU
Ferguson, Scot – UNR
Ferguson, Todd – UNR
Fowers, Beth – USU
Gearhart, Jessica – UNR
Hoskins, Eric – UNR
Hourihan, Erin – UNR
Jahn, Kurt – UNR
Kaufman, Max – USU
Klinger, Robert – USU
Lattin, Mark – UNR
Leonis, Juan – UNR
Logan, Tyler – USU
Lumpkin, Will – UNR
Preece, Daniel – USU
Sanchez, Monica – ARS-R
Scatchard, Ross – USU
Shepard, Sara – ARS-R
Sivy, Kelly – USU
Souna, Kia – USU
Taylor, Travis – USU
Teson, Brad – USU
Thornley, Nico – UNR
Toth, Joe – UNR
Vaquerizo, Aldo – ARS-R
Varnon, John – UNR

7. Volunteers

Bell, Brian – USU
Burnham, Heather – USU
Dhaemers, Jessica – UNR
Goergene, Erin – UNR
Leonard, Eamonn – USU
Loynes, Katie – USU
Mukherjee, Jayanti – USU
Newbold, Scott – USU
Pekas, Kristen – USU
Rau, Ben – UNR
Rayburn, Andrew – USU
Rieder, Julie – USU
Scherpenisse, Dara – USU
Sneddon, Penny – USU
Thygerson, Tonya – USU